"While human ingenuity may devise various inventions to the same ends, it will never devise anything more beautiful, nor more simple, nor more to the purpose than nature does, because in her inventions nothing is lacking and nothing is superfluous"

Leonardo da Vinci (1452-1519)

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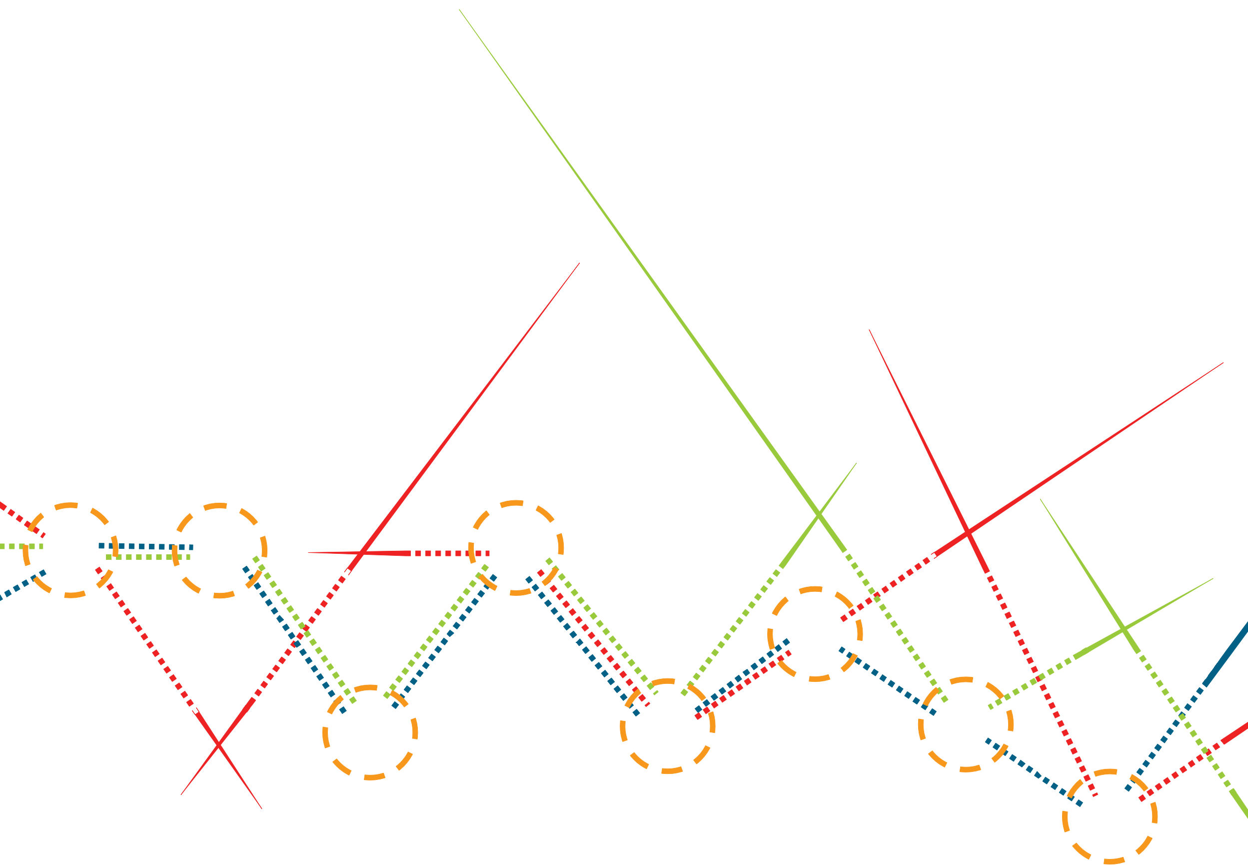
Towards the LIVING envelope *Biomimetics for building envelope adaptation* Lidia BADARNAH KADRI

Towards the LIVING envelope

Biomimetics for building envelope adaptation



Lidia BADARNAH KADRI

Towards the LIVING envelope
Biomimetics for building envelope adaptation

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Proefschrift

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door

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Bachelor of Architecture, Technion - Israel Institute of Technology
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Summary

Towards the **living envelope**: *biomimetics for building envelope adaptation*

Lidia Badarnah Kadri
Delft University of Technology

Several biomimetic design strategies are available for various applications, though the research on biomimetics as a design tool in architecture is still challenging. This is due to a lack of systematic design tools required for identifying relevant organisms, or natural systems, and abstracting the corresponding generic principles for implementation in design concept generations for building envelopes.

A major challenge in current strategies is the filtering of the wide possibilities that nature provides, especially for architects who have limited biophysical background. In order to find design solutions from nature, the requirements of the artificial system have to be defined, and then analogue systems in nature that perform similar functions need to be identified. The design generating tools should support the transitions between the domains, especially the identification of biological analogies and their abstraction.

To this end, the current thesis proposes a strategic methodology, referred to as the *living envelope* methodology, for the generation of design concepts. The proposed methodology provides an exploration and investigation platform for architects. It assists channelling the way from technical challenges, defined by the demands on the living envelope, through functional aspects and various strategies found in nature. Furthermore, the proposed methodology provides several phases of categorizations that funnel at the end into a single imaginary organism/system, referred to as *imaginary pinnacle*, which has the successful dominant features of the desired living envelope. The various phases and

sub-phases of the methodology facilitate the transitions between the various phases of the design process, with a special attention to the representation of biophysical information, identification and abstraction of principles, and their systematic selection. Systematic exploration models are developed for the biophysical information representation, and unique schemes and flow charts that provide user-friendly design tools are developed and presented.

For the validation of the methodology and the assessment of its generality, four important environmental aspects that need to be managed by the building envelope are applied to the methodology: (1) air – to manage ventilation, which is required in order to provide high indoor air quality and to prevent air stagnation; (2) heat – to maintain a thermal comfort for the occupants; (3) water – to gain and make use of condensed water in arid areas; and (4) light – to provide a shading system with minimized undesired heat gain and maximized daylight. For each of the four aspects exemplary design concepts are successfully generated. It is worth noting that the aim of investigating these environmental aspects is not to provide detailed design solutions; rather the presented examples of the generated design concepts examine the generality of the implementation of the methodology. In order to further assess the generality of the proposed methodology, a qualitative example that combines all four environmental aspects is introduced.

The results of the exemplary design concepts show the advantage of the proposed living envelope methodology. The methodology is capable to generate design concepts with specified initial challenge set by the user (architect). Moreover, the design cases open new perspectives for new possible technical solutions for building envelopes, and the potential to realize a new class of innovation and lay a functional foundation in architecture: a bio-inspired, climatically oriented, and environmentally conscious.

Samenvatting

Naar een **levende enveloppe**: *biomimetics voor gebouw enveloppe aanpassingen*

Lidia Badarnah Kadri
Technische Universiteit Delft

Ondanks het feit dat er verschillende biomimetische ontwerpstrategieën beschikbaar zijn voor verschillende toepassingen, is het onderzoek naar biomimetics als ontwerptool voor de architectuur nog steeds een uitdaging. Dit is te wijten aan een gebrek aan systematische ontwerptools voor de identificatie van relevante organismen, of natuurlijke systemen, alsmede het abstraheren van de overeenkomstige algemene beginselen voor de implementatie, met als uiteindelijk doel ontwerpconcepten te genereren voor gebouwen.

Vooral voor architecten met een beperkte biologische achtergrond is het filteren van de brede mogelijkheden die de natuur biedt een belangrijke uitdaging met de huidige strategieën. Om ontwerpoplossingen in de natuur te vinden moeten de eisen van het kunstmatige systeem vastgesteld worden, waarna analoge systemen in de natuur met gelijkwaardige functies geïdentificeerd moeten worden. De tools om ontwerpen te genereren moeten de overgang tussen beide domeinen ondersteunen, met name de identificatie van biologische analogieën en hun abstracties.

Tot nu toe stelt het huidige proefschrift een strategisch bedoelde methoden voor, genaamd de “levende enveloppe methode”, voor het genereren van ontwerpconcepten. De voorgestelde methode biedt een verkennend en onderzoekend platform voor architecten. Het helpt het in banen leiden van technische uitdagingen, gedefinieerd door de eisen van de levende enveloppe, naar in de natuur gevonden functionele aspecten en verschillende strategieën. Bovendien biedt de voorgestelde methodologie verschillende fasen van

categorisering welke uiteindelijke leiden tot een eenduidig denkbeeldig organisme / systeem, aangeduid als het denkbeeldige hoogtepunt, welke de succesvolle dominante kenmerken heeft van de gewenste levende envelop. De verschillende fasen en sub-fasen van de methodologie vergemakkelijken de overgangen tussen de verschillende fasen van het ontwerpproces, met een bijzondere aandacht voor de representatie van biologische informatie, identificatie en abstractie van principes, en hun systematische selectie. Semantisch gestructureerde exploratie-modellen zijn ontwikkeld voor de biologische informatie vertegenwoordiging, en gebruiksvriendelijke design tools met unieke programma's en stroomdiagrammen zijn ontwikkeld en worden gepresenteerd.

Voor de validatie van de methodologie en de beoordeling van de algemeenheid, zijn vier belangrijke milieuaspecten toegepast die door de gebouw enveloppe moeten worden beheerd: (1) lucht - ventilatie, welke nodig is om een hoge kwaliteit van de binnen lucht te bieden en luchtstagnatie te voorkomen, (2) warmte – om een thermisch comfort voor de bewoners te behouden; (3) water - om condenswater te winnen en te gebruiken in droge gebieden en (4) licht - om schaduw te verschaffen om zo minimale opwarming te verkrijgen met behoud van maximaal daglicht. Voor elk van de vier aspecten worden met succes voorbeeld ontwerpen gegenereerd. Het is vermeldenswaardig dat het doel van het onderzoek naar deze milieuaspecten niet is om gedetailleerde ontwerp oplossingen te bieden, maar veeleer de voorbeelden van de gegenereerde ontwerpconcepten te onderzoeken op algemeenheid van uitvoering van de methodiek. Om verdere beoordeling van de algemeenheid van de voorgestelde methodologie te beoordelen, wordt een kwalitatief voorbeeld geïntroduceerd dat alle vier milieuaspecten combineert.

De resultaten van de ontwerpvoorbeelden tonen de voordelen van de voorgestelde methode "levende enveloppe". De methodiek is in staat om design concepten te genereren aan de hand van door de gebruiker (de architect) gespecificeerde eerste set eisen. Bovendien bieden de ontwerpvoorstellen nieuwe perspectieven voor nieuwe technische oplossingen voor de bouw enveloppe, met het potentieel om een nieuwe klasse van innovatie te realiseren en een functionele basis in de architectuur te leggen: bio-geïnspireerd, klimatologisch georiënteerd, en milieubewust.

Introduction

Chapter 1

1.1 Motivation

Buildings are structures of defined spaces that protect people and their belongings from the exterior environment, among which are the direct harsh weather conditions, such as wind, rain, and excess sun radiation. Buildings evolved from primitive structures providing mere shelters to sophisticated structures responding to environmental context, where various features and elements have emerged from necessity to raise comfort and quality of life. Vernacular architecture exhibits a good example of buildings that reflect the environmental context, where regional differences of the built structure are results of their response to culture, climate, and geographical location [Zhai & Previtali 2010]. For example, buildings in hot and humid climates, in hot and dry climates, or in cold climates, have different features that respond according to the environmental context [Lechner 2009]:

- Massive walls, small windows, light colours, close clustering for shade, are common features in hot and dry climates; these features minimize solar radiation absorption, allow heat dissipation during the night, and provide outdoor shaded spaces.
- Large windows, large overhangs, shutters, high ceilings, and light construction materials, are common features in hot and humid climates; these features enhance airflow to increase the rate of evaporative cooling, increase ventilation, and protect from solar radiation and rain.
- Few windows, use of wood rather than stone, low ceilings, minimum surface-area per unit volume, are common features in cold climates; these features retain and conserve heat, and prevent heat dissipation through the building envelope.

During the twentieth century, the modern movements in architecture resulted in buildings that look the same despite their location and climate conditions, where the term international architecture has been applied. The objective of these modern movements is to combine functionalism with aesthetic principles for architectural design, and to implement the advanced technologies of their era. The extensive use of glass and metal and other new industrialized materials in buildings dramatically increased comfort demands in buildings, which required new techniques to manipulate the indoor climate. As a result, various mechanical systems were introduced to manipulate the indoor climate, which, in turn, required a great deal of energy. The increasing environmental awareness, precipitated by the oil crisis of the 1970's, brought new demands for energy efficiency and function-oriented solutions, such as energy saving, natural ventilation, insulation, and sun protection [Lechner 2009]. As these new demands emerged, a new concept has evolved: *Sustainable development*. Environmental, social, and economic considerations are the fundamental aspects for sustainable development [Brundtland 1987]. The evolving sustainability approach to building aims to energy and resource efficiency, and environmental friendly outputs. It can be achieved by using "*the best of the old and the best of the new*" [Lechner 2009]; thus, by using modern sciences and technologies combined with traditional principles that respond to human needs and environmental conditions. This approach may lead to functional design solutions that interact with the environment, where technology becomes an integral part of the environment. Human is an integral part of the environment as well, "*I live on Earth at present, and I don't know what I am. I know that I am not a category. I am not a thing - a noun. I seem to be a verb,* *an evolutionary process - an integral function of the universe,*" [Buckminster Fuller *et al.* 1970] where buildings should create a continuation between human and environment, and maintain a certain level of interaction. In this context, the building envelope is the physical part that could be considered as the medium between human and environment, which might influence the level of interaction between human needs and environmental conditions.

Nowadays, building envelopes are associated with a wide range of innovative technologies that significantly influence the visual expression of the building, e.g. Kunsthaus Graz [Bogner 2004]. Additionally, these technologies, in particular cases, have a functional role in providing a satisfactory indoor climate for the occupants, e.g. CH2 council house [CH2 2012]. The deployment of such functional solutions has led to the use of the term *adaptive* in an environmental context. Thus, an adaptive building envelope can manipulate the various environmental aspects for better performance and for the satisfaction of its occupants.

Adaptation strategies are considered to be a key aspect for the design of building envelopes that can accommodate the environmental changes with less energy consumption. It is proposed that the implementation of successful adaptation strategies inspired from nature can result in adaptive building envelopes that "behave" as living organisms or natural systems that accommodate the dynamic environmental changes; in other words, the envelope should be able to regulate and manage, among others, air, water, heat and light. To this end, successful strategies could be obtained from nature, which presents an immense source for adaptation strategies [John *et al.* 2005]. The challenge for architects, in this context, is to transform these adaptation strategies from nature into successful technological solutions for building envelope adaptation.

1.2 Main objectives

- To introduce a novel selective methodology for the generation of design concepts, inspired by nature, for building envelopes that are able to regulate various environmental aspects.
- To introduce environmental adaptation strategies from nature, which are related to regulation challenges of the building envelope.
- To provide a proper representation of the biophysical information to be accessible by architects.

1.3 Research questions

The main question addressed in this dissertation is:

> *How to generate design concepts for building envelopes that regulate environmental aspects, based on adaptation strategies from nature?*

In order to answer the main research question, the following sub-questions are addressed in the subsequent chapters:

What are the environmentally related functions of the building envelope that fulfil the demands and requirements by occupants?
What are the main merits and limitations of current methodologies that can be used for the development of designs inspired by nature?
What are the relevant adaptation strategies and mechanisms found in nature, for implementation in building envelopes?
How to represent the identified adaptation mechanisms and strategies from nature for the convenient accessibility by architects?
What type of design strategy is needed for generating design concepts based on mechanisms and strategies found in nature?
How to assess the generality of the proposed methodology, and what are its merits and limitations?

1.4 Approach and methodology

The current research combines the two disciplines, architecture and biophysics, for the objective of developing a biomimetic design methodology for environmentally regulating building envelopes. The research approach investigates organisms that provide self-regulating living environments with the ability to regulate internal and external conditions. The proposed approach is not nature *imitation*, but rather abstracting, transforming and developing principles, methods, and strategies carried out by organisms or natural systems to realize design concept solutions for building envelopes, thus nature *emulation*.

The convergence of challenges of the building envelope with strategies and mechanisms found in nature, through biomimetics, is aimed towards the design of living envelopes that regulate the surrounding environmental aspects for the occupant's comfort. This concept of research approach is illustrated in Figure 1.1.

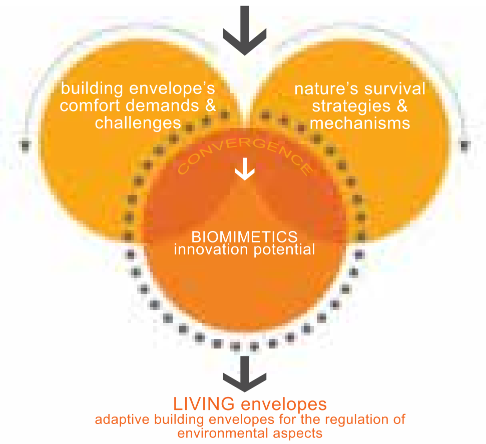

Figure 1.1

Scheme of the approach towards the *living envelope*: convergence of the building envelope's comfort demands & challenges with nature's survival strategies & mechanisms through biomimetics.

The proposed methodology has to be selective in order to enable managing the large sample size nature provides. Thus, the methodology requires investigating adaptation strategies and mechanisms found in nature, and distinguishing various functional aspects relevant for adaptation, which are classified in an exploration model and selective design tools leading to the generation of design concepts for building envelopes. In order to assess the generality of the proposed methodology, design concepts of four major environmental aspects, air, heat, water, and light, need to be generated for building envelope regulation, and possible integration of multiple environmental aspects need to be addressed. In order to achieve the main objectives of this research, the following steps are carried out:

- Analyse design methods existing in literature, and summarize their merits and limitations.
- Investigate adaptation strategies and mechanisms found in nature in the context of air, heat, water, and light regulations.
- Distinguish important functional aspects for adaptation, and provide a relevant representation of the biophysical processes for potential application in building envelopes.
- Encapsulate and categorise all relevant functional aspects in a selective flow chart.
- Provide a systematic selective strategy for distinguishing the features to be applied in the design concept.
- Consider different environmental aspects to assess the generality of the proposed methodology.

1.5 Outline

The schematic representation of the thesis outline is presented in Figure 1.2. Chapters 2 and 3 present the background and the developed methodology, respectively. Chapters 4, 5, 6, and 7 have a similar structure and elaborate on four environmental aspects: air, heat, water, and light. Furthermore, a detailed exploration model is provided, for each chapter, based on the *living envelope methodology*, where strategies, mechanisms, and principles are summarized and developed into concept design solutions for adaptive building envelopes. Chapter 8 discusses the integration of the four environmental aspects, air, heat, water, and light, simultaneously. Finally, chapter 9 concludes on the overall work of the thesis.

……………………………………...………………………………Chapter 2………..

An overview on adaptive architecture and building envelopes, different adaptation configurations, and demands and requirements the building envelope needs to fulfil are given in chapter 2. Adaptation is an important design strategy that can help accommodate the variations facing the building envelope. An adaptive building envelope should regulate air, heat, water, and light, as a response to occupant demands and the environmental changes occurring in the exterior surroundings.

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In chapter 3, a methodology for the design of adaptive building envelopes inspired from nature is presented. Such envelopes are referred to, in this work, as living envelopes and they are characterized by interaction with, and responsiveness to, the environment. Nature provides a large database of adaptation principles and methods, including those at the interface with the environmental conditions. Thus, a structured selective method of investigation is presented in order to increase the efficiency of the design process, and to select for appropriateness of solutions found in nature. The presented design process consists of a preliminary design phase and an emulation phase. The various sub-phases of the design process are discussed and presented in unique schemes and flow charts that provide a user-friendly tool of the design method.

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………………………………………………………………………………Chapter4………..

One of the main objectives of the living envelope is to manage ventilation, which is required in order to provide high indoor air quality and to prevent air stagnation. Chapter 4 discusses air regulation mechanisms in nature for a potential application in building envelopes for environmental adaptation. Various respiratory organs in nature have evolved to facilitate an efficient exchange of gases. Air exchange and movement are significant functions in nature, as organisms need oxygen to survive. The efficient active and passive solutions in nature might promote the design of innovative hybrid ventilation systems for building envelopes, and result in better indoor air quality with less energy consumption. A test case with airflow simulations is presented for methodology validation.

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………………………………………………………………………………Chapter5………..

The living envelope has to maintain a thermal comfort for the occupants. Current technologies for buildings consider the envelope as a thermal barrier or a shield that has to be insulated to prevent heat loss and allow it to be open to dissipate heat if necessary. Chapter 5 discusses more efficient thermoregulation solutions that are found in nature. Organisms can manipulate their body temperature by physiological or behavioural means as an adaptive response to the environmental changes. In this chapter performance taxonomy of organisms that facilitate thermoregulation in nature is presented, and their possible application in building envelopes is discussed. Moreover, an application case of such taxonomy for adaptive building envelopes is obtained.

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Water regulation in buildings has been facing real challenges with the increasing environmental awareness during the last decades. Providing water supply and waste management systems for buildings are major concerns for water regulation. Chapter 6 investigates water regulation mechanisms found in nature with the objective of implementation in building envelopes. During water regulation in nature, there exists a continuous balance between water loss and water gain. Various factors exist that affect this balancing process. An overview of water regulation mechanisms in nature for water loss and gain, and for water dynamics is given in this chapter. A design concept of water harvesting surface for building envelopes is generated based on the living envelope methodology.

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……………………………………………………………………………Chapter7………..

The living envelope has an important role to regulate light. Managing light might become a real challenge when several elements are considered simultaneously, e.g. minimizing heat gain, while maximizing daylight, yet considering glare. Shading systems are attached to buildings in order to control the amount of radiation on the envelope. Current technologies provide various solutions to reduce glare, by directing or blocking light, which often have a limited adjustability to cover the whole solar radiation path. The rotation of sun and earth creates unique light habitats on earth, where organisms have adapted special strategies and mechanisms that can manipulate light interception in order to deal with different light conditions in their environments. Chapter 7 presents various strategies and mechanisms for light regulation in nature. A medium can transmit, absorb, reflect, direct, emit, and diffuse light. Variations in the medium properties affect light intensity and interception. An adaptive shading system inspired from leaves is generated as another test case for the living envelope methodology.

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……………………………………………………………………………Chapter8………..

Each of the preceding chapters, 4-7, considers a single environmental aspect. However, living envelopes are required to regulate multiple environmental aspects, simultaneously. Therefore, multi-regulation aspects that integrate design challenges from air, water, heat, and light, simultaneously, are assessed and discussed in chapter 8. For convenience, a polar user-friendly integrated exploration model is presented.

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……………………………………………………………………………Chapter9………..

Finally, the main highlights, results, and final remarks are concluded in chapter 9. The proposed living envelope methodology is a strategic methodology that creates an exploration and investigation platform for the architect and helps channelling the way from technical challenges, through functional aspects in nature, to various possible strategies found in nature. Unique schemes and flow charts that provide user friendly design tools were developed and presented. The results of the exemplary design concepts (presented in chapters 4-7) show the advantage of the proposed living envelope methodology. The design generating tools increase the efficiency of the design process, and they are capable to generate design concepts with a specified initial challenge set by the user. Moreover, the design cases opened new perspectives for new possible technical solutions for building envelopes, and the potential to realize a new class of innovation and lay a functional foundation in architecture: a bio-inspired, climatically oriented, and environmentally conscious.

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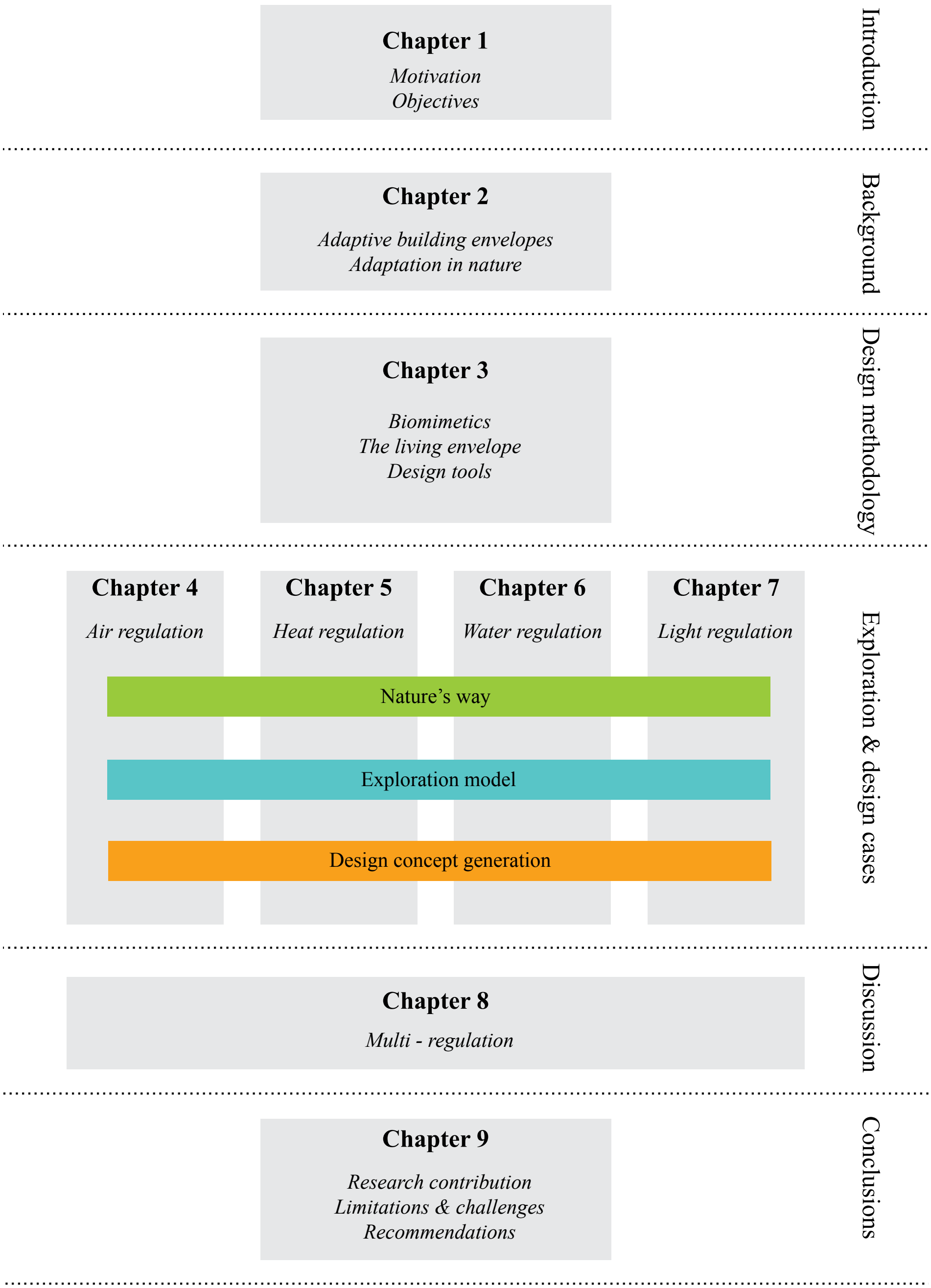


Figure 1.2
Thesis Outline.

References

Bogner, D. (ed.), [2004]. *A Friendly Alien: Ein Kunsthaus fur Graz*, Ostfildern-Ruit: Hatje Cantz.

Brundtland [1987]. *Our Common Future, World Commission on Environment and Development*, Oxford.

Buckminster Fuller, R., Angel, J., and Fiore, Q., [1970]. *I seem to be a verb: environment and man's future*, New York: Bantam.

CH2, council house, Melbourne. *CH2: How It Works?*, available online at: http://www.melbourne.vic.gov.au/Sustainability/CH2/aboutch2/Documents/CH2_How_It_Works.pdf (retrieved July 2012)

John, G., Clements-Croome, D., and Jeronimidis, G. [2005]. Sustainable building solutions: a review of lessons from the natural world. *Building and Environment*, **40**, pp. 319-328.

Lechner, N., [2009]. *Heating, Cooling, Lighting: sustainable design methods for architects*, 3rd ed., New Jersey: John Wiley & Sons Inc.

Zhai, Z. & Previtali, J.M., [2010]. Ancient vernacular architecture: characteristics categorization and energy performance evaluation. *Energy and Building*, **42**, pp. 357-365.

Background

Chapter 2

2.1 Introduction

As new demands for comfort emerged in buildings during the 1970's, adaptation concepts became more prevalent. The term adaption is mentioned in architecture to describe the process performed by systems in which specific properties of a building are changed within a specific time frame in order to manage changing environmental conditions or occupants' demands. The environment is in a constant flux over time and space, thus there is a need to accommodate and manage the environmental changes for the occupant's satisfaction. For example, "*an ideal cladding system would have quite different thermal and optical properties at different times of the day and night, at different outdoor temperature conditions, and in summer and winter*" [Gregory 1986].

Three categories can be defined for the performance level of adaptation based on the dimension of change and the functional features of each category, as illustrated in Figure 2.1: (a) flexible adaptation – 2D change of surface orientation; (b) transformable adaptation – 3D change of spatial configuration; and (c) responsive adaptation – 4D change of time and space. The proposed classification aims to reduce the overlap of adaptation definitions found in literature (e.g. Lelieveld *et al.* 2007), as well as it emphasizes the importance of the dimension of change to define each adaptation category.

Brief elaborations on the adaptation categories are presented in Table 2.1. The table presents variables, attributes, and featuring elements of each category; it also classifies exemplary and representative projects in literature based on the proposed classification. Further details on some of the representative projects are discussed in section 2.6.

Figure 2.1

Representation of the relationship between the three categories for adaptation, suggesting that: *Transformable* contains *Flexible*, and *Responsive* contains both *Flexible* and *Transformable*.

Besides the definition and the proposed classification of adaptation, this chapter provides background on essential subjects of the current research. The objectives of an adaptive building envelope, environmental context, and user's demands are given in section 2.2. Current solutions for adaptation are presented in section 2.3. Conflicts between requirements are elaborated in section 2.4. Adaptation solutions in nature, in general, are discussed in section 2.5. Solutions inspired by nature for building envelope adaptation are given in section 2.6. Finally, the concluding remarks are presented in section 2.7.

Table 2.1 The variables representing the three different categories for adaptation.

Adaptation	Variables, attributes, featuring elements ……………………...... Exemplary/representing projects
Flexible 2D change: referring to a change in surface orientation/configuration. Adjusting specific elements of the building for change in layout (e.g. sliding doors, or walls), or for component configuration (e.g. louvers). These adjustments are mainly operated by the occupant.	Layout, appearance, lighting, walls, windows, operable elements, parts, components, joints, hinges, sliding doors or walls, louvers, etc. ……………………...... *The Rietveld Schröder House*, Utrecht (Netherlands) 1924, Gerrit Rietveld [UNESCO 2011].
Transformable 3D change: referring to spacious/formal configurations of the structure. Change space	Space, form, pattern, structure, actuators, etc. ……………………...... *Expanding Geodesic Dome*, New Jersey, USA 1991, Chuck Hoberman [Kronenburg & Klassen 2006].
Responsive 4D change: referring to functional aspects changes in real-time Referring to change with the factor of time React to stimuli	System, material, environment, user demand, building envelope, sensors, actuators ……………………...... *Thermochromic glass* [Gao *et al.*2012]. *The InteractiveWall*, TU Delft, Netherlands 2009, HyperBody research group [Hosale & Kievid 2009]. *The Aegis HypoSurface*, Birmingham (UK) 1999, Mark Goulthorpe [Sterk 2003].

2.2 Adaptive building envelopes

The building envelope represents the interface between the exterior environmental factors and the interior demands of the occupants [Del Grosso & Basso 2010]. An adaptive building envelope should respond to changing environmental impacts occurring in the exterior environs while managing indoor climate. The concept of adaptive building envelopes aims at reduced energy consumption and increased occupant comfort and control. Adaptive building envelopes should have adaptation strategies to anticipate exterior environmental variations as well as interior activities and their interactions with inhabitants (Figure 2.2). Such strategies will allow a proper response to a wide range of situations for better performances and occupant comfort.

New proposals for adaptive building envelopes have been emerging since the last century; some are theoretical, yet potentially applicable. For example, Davies [1981] proposed the “Polyvalent wall”; it consists of thin layers that have the ability to absorb, reflect, filter, and transfer energies from the environment. In the 1930’s, Le Corbusier introduced “the house of exact breathing” as an adaptive concept, where he elaborated on the wall that manages the interior environment through its cavity [Le Corbusier 1991]. This concept was never carried out because of the lack of technology at that time for such a futuristic idea.

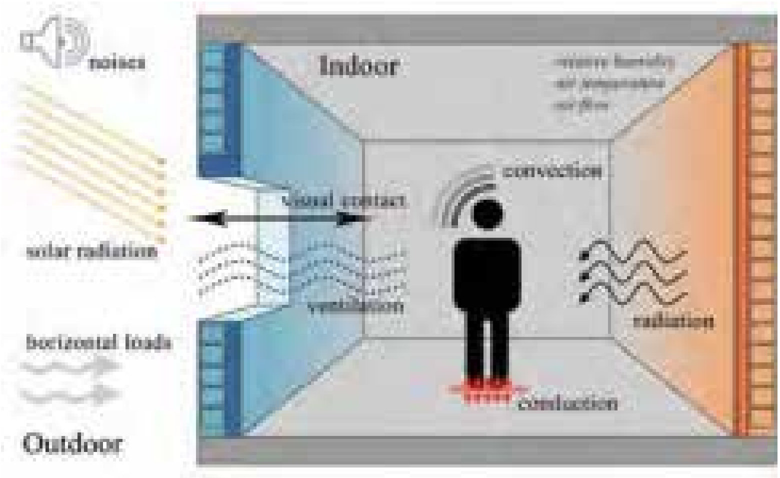


Figure 2.2
The interactions between the occupant, the environment, and the building.

The building envelope as an interface between the exterior environment and the occupied interior spaces.
Table 2.2

User requirements & demands (inside)	Interface (Building envelope)	Environmental factors (outside)
Light Illuminance 300- 500 lx Prevent Glare	Reflect Absorb Redirect Diffuse	Solar radiation Clear sky 50000 lx
Temperature Winter 20- 23°C Summer 22- 27°C	Dissipate Gain Conserve	Air temperature (-20) - 40°C
Air quality CO_2 content < 1500 ppm 30m³/h person	Filter Exchange	Air quality CO_2 350- 800 ppm dust
Air speed Velocity < 0.2 m/s	Modify flow	Air movement 0- 25 m/s
Humidity 30- 60%	Absorb Collect Evaporate	Humidity
Noise Max 30- 45 dB(A)	Dampen	Sounds/noises 30- 90 dB

Users' demands and activities, as well as the environmental factors affect the preferred air movement, humidity, temperature, solar radiation, air quality, noise, etc. Available standard regulations for buildings state the demanded parameters for comfort according to occupants' physical state (e.g. Fanger 1972). Various strategies that can be implemented in building envelopes to manipulate the environmental factors for comfort are presented in Table 2.2. The table shows that the adaptive building envelope, acting as an interface, may have different strategies or combination of strategies to manipulate the environmental factors, e.g. humidity could be adjusted by absorption, collection, evaporation, or any combination of these three strategies.

In the present work, focus is given on four main functions of the adaptive building envelope: (1) air regulation; (2) water regulation; (3) thermoregulation; and (4) light management. These four were chosen amongst all because of their significant influence on comfort conditions. These functions are studied in details in chapters 4-7, respectively. Sections 2.2.1 and 2.2.2 elaborate on some of the basic users' demands and environmental factors, respectively.

2.2.1 User's demands and activity

In addition to the comfort demands by occupants, various behaviours of the occupants and their presence affect the demands from the building envelope, e.g. the level of activity affects the preferred parameters for comfort such as temperatures and humidity. Available standard regulations for buildings (such as ASHREA and Fanger) state the required parameters for comfort according to occupant's physical state (clothing & activity). Nowadays, the *adaptive thermal comfort*[1] concept is gaining more attention, where occupant's adaptation (acceptance & behaviour) is taken into account, and results in a wider acceptable temperature ranges [Linden *et al.* 2006, Nicol & Humphreys 2002]. A convenient way to understand some interrelationships of comfort is by means of the *psychrometric chart*[2] given in Figure 2.3.

2.2.2 Environmental factors

The environment is constantly changing and creating new challenging situations to cope with. Air movement, relative humidity, air temperature, solar radiation, air quality, and noises are considered basic environmental factors affecting the building and its occupants. The interplay of air temperature, humidity, and air velocity significantly affect perceived comfort. Brief backgrounds on some of the factors affecting occupant comfort demands, relevant to the succeeding chapters, are given as follows.

2.2.2.1 Air movement

A basic purpose of air movement is ventilation and cooling, where it influences heat loss rate by convection and evaporation. Air movement may raise unpleasant and disruptive situations at high speeds (called draft). The comfortable range is from 0.1 to 0.3 m/s,

1 "When a change occurs causing thermal discomfort, people react in such a way that their thermal comfort is reestablished." [Auliciems 1983].

2 A psychrometric chart is a graph of the thermodynamic parameters of moist air at a constant pressure, often equated to an elevation relative to sea level.

and starts being noticed from 0.3 to 1.0 m/s where comfort starts depending on occupant activity. Moving hot air (above 37°C) heats the skin by convection while cools by evaporation. At high temperatures, the total cooling effect is reduced [Lechner 2009]. Air movement may also be applied to generate mechanical energy. The ancient Persians used this energy source to pump water and grind wheat. Nowadays, giant wind farms are found in developed countries (e.g. the Netherlands, U.S., Germany), consisting of turbines raised on high columns to catch the highest possible wind speeds. This strategy is applied in buildings, by adding big turbines on the envelope, to enhance ventilation and generate clean energy [Lechner 2009].

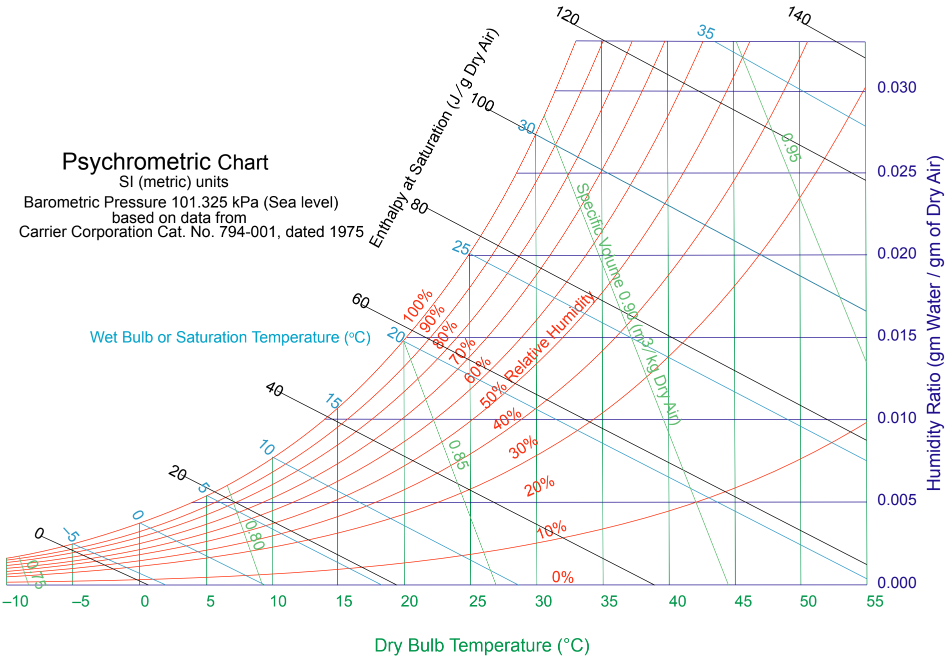


Figure 2.3

Psychrometric chart for sea level pressure using SI units. Courtesy of Arthur Ogawa [2009].

2.2.2.2 Relative humidity

Relative humidity and air temperature vary from climate to climate, and individuals vary to what they find acceptable. ASHRAE [2004] defines thermal comfort as: "*that condition of mind which expresses satisfaction with the thermal environment*". Though occupant activity and clothing affect comfort levels, ASHRAE guidelines recommend for normal clothing 30-60% relative humidity. Maintaining the relative humidity in the recommended range avoids undesired comfort situation, like dryness of mucous membranes, eyes, and skin at low relative humidity [Sunwoo *et al.* 2006], and moisture accumulation and respiratory discomfort at high relative humidity [Fang *et al.* 1998, Bornehag *et al.* 2004]. Airflow and temperature are significant factors that can moderate indoor humidity levels for better comfort conditions.

2.2.2.3 Air temperature

The ASHRAE guidelines recommends for normal clothing 20-23 °C in winter, and 22-27 °C in summer. Air temperature influences body heat gain and loss via convention; the larger the gradient (air temp. – body temp.), the greater the heat loss is. Both air temperature and the mean temperature of surrounding surfaces affect thermal comfort, where the body warms up by radiation. High room temperatures enhance evaporation through skin for cooling, thus combined with high relative humidity will affect comfort. Additionally, clothing and activity types influence perceived temperature from the surroundings.

2.2.2.4 Solar radiation

Sun is the main source of radiation, where azimuth and altitude angles change over time. Solar radiation is an ideal energy source for its presence everywhere throughout the year, with different quantities, and environmentally friendly characteristics [Compagno 2002]. Radiation absorption, reflection, and transmission are the basic parameters to describe the permeability inside the building, whereas orientation is a significant factor influencing light distribution and intensity in the building. An even distribution of light may result in glare, which causes eye fatigue and distraction.

2.3 Current solutions for adaptation

The emerging new technologies, in particular information technology, make it possible for buildings to self-adjust and respond to varying environmental conditions [Wigginton & Harris 2002]. Mechanical services attachment and integration and the implementation of responsive materials are distinguished as current means for climate adaptation in buildings.

2.3.1 Mechanical services

Mechanical services are one of the ways to manipulate environmental aspects for adaptation. Technology, use, and maintenance, are important factors for the functioning of the mechanical services. They can be either attached to or integrated in the envelope.

The attached services could be either part of the overall design concept – attached on the exterior wall, or as a separate and isolated solution attached at the interior/exterior wall, such as an air-conditioning unit. The separation between the structure and the mechanical services can influence the circulation and communication among persons, information and products in buildings [Banham 1984]. Banham claims that history ignored the "technological art of creating habitable environment" and focused on "*the external forms of habitable volumes as revealed by the structures that enclose them*" [Banham 1984]. Integrating technology into the overall design process can influence the results for a more innovative and sustainable solutions [Watson 1997].

The integrated services approach considers the building envelope as a functional layer, where services are part of the structural composition. The interdependency of the different elements of the envelope has a major effect on the level of adaption to the various environmental factors. According to Baier, "... *The same can be observed in buildings: the higher the applied technology, the more complex dependencies and a higher resistance* *to adaptation processes can generally be stated*" [Baier & Meyer-Miethke 1975].

2.3.2 Building materials

Materials have a great influence on the performance of systems due to their molecular structure. The integration of advanced and responsive materials in building envelopes can enhance the adaptation in real-time for a better performance. A wide range of smart materials has been emerging throughout the last years, where it has a high potential in the construction field [Addington & Schodek 2005]. For example, phase change materials applied in buildings for energy conservation purposes improve thermal distribution and cost and space effectiveness. A new class of materials is being developed for potential use in buildings, e.g. the investigation of the use of shape memory alloys (SMA) and shape memory polymers (SMP) to realize a shape adaptable architecture for various purposes [Lelieveld & Voorbij 2009].

2.4 Conflicts between requirements

While the strategies for dealing with environmental factors are many, the variations occurring in the environment creates a number of conflicting situations that must be concomitantly addressed: "*Modern facades systems need to fulfil a wide range of different often conflicting requirements – such as maximum daylight optimisation and glare protection, thermal inertia and light-weight structures – with inverted priorities according to the seasons*" [Gosztonyi *et al.* 2010]. The daylight required on a summer day may lead to a conflict with the solar screening system, whereas the desired high solar radiation in winter may result in glare. The adaptive building envelope is required to manage such conflicts and find a solution, where prioritizing the different factors is recommended for such scenarios. The priorities of the factors change according to the particular scenario, where the conflicts are utilized for an optimal performance. Accordingly, the adaptive building envelope may manoeuvre between different strategies to achieve the optimal performance. Thus, the adaptive building envelope should have dynamic characteristics to avoid conflicts between requirements and provide optimal performance.

Current dynamic characteristics and design technologies are applied in various fields of science. However, they are rarely applied in construction despite their high potential in reducing energy consumption. A possible reason is the lack of interdisciplinary collaborations between architects and specialists from other fields. One interdisciplinary approach that offers high potential for solving the dynamic nature of optimal adaptation is the emerging design discipline of Biomimetics - learning from and emulating nature. One reason this holds such promise for adaptive building envelopes is the frequent indication in literature to analogies from nature for adaptation [Gregory 1986, Wadhawan 2007, Compagno 2002]. Adaptation is a major aspect in living organisms for effective and efficient strategies that promote survival. Investigating aspects in living organisms and finding their analogies in technologies could promote new designs for adaptive building envelopes that are more efficient, less energy demanding, and can adapt to the different environmental changes in the short or long range [Badarnah & Knaack 2008a, Badarnah & Knaack 2008b, Badarnah *et al.* 2010], thus preventing conflicts between requirements.

2.5 Adaptation solutions in nature

As architects and engineers try to maintain a comfort state inside the buildings despite the changes of the environmental conditions, many living organisms seek physiologically tolerable conditions (what humans call "comfort"), called homeostasis in biology. *Homeostasis*[3] is one of the fundamental characteristics of living organisms. There are several factors that are constantly regulated by the body of an organism to achieve homeostasis, including: concentrations of nutrients, oxygen, salts, wastes, heat, pressure, and volume [Hill *et al.* 2008]. These factors are manipulated through the following processes for homeostasis:

- Gas regulation: Respiration / Ventilation
- Water and osmotic regulation: Osmoregulation
- Heat regulation: Thermoregulation

Living organisms have developed through evolution adaptation strategies to cope with different environmental aspects. Their adaptation may occur at various scales of time: throughout the day (e.g. solar tracking by sunflowers); throughout the seasons (e.g. seasonal changes in blubber distribution in seals [Rosen & Renouf 1997]); or throughout evolution (e.g. human skin colour). Adaptation is especially obvious in the organisms able to survive harsh and challenging environment conditions. These environments are called extreme environments, because of their extreme influential factors, which include: extremes of temperature, humidity, solar radiation, pressure, and other environmental factors. Such factors have necessitated the evolution of unique adaptations in terms of physiology, morphology, and behaviour [Louw & Seely 1982]; the physiological and morphological adaptations reflect functional features that help organisms to adapt to their environment, whereas behavioural adaptations relate to the actions done by organisms in order to survive. Each of these is discussed in more detail below.

2.5.1 Physiological

Physiological adaptation is "*an organismic or systemic response of an individual to a specific external stimulus in order to maintain homeostasis*" [Biology-online dictionary]. "*Basically, homeostasis can be considered paramount for the successful adaptation of the individual to dynamic environments, hence essential for survival*" [Vargas *et al.* 2009]. Physiology is about the regulation of the different functions that allow them to adjust to the environmental changes – "*how they are correlated and integrated into a smooth-functioning organism*" [Schmidt-Nielsen 2007]. An example for a physiological adaptation is the salinity tolerance of the mangroves. Mangroves (Figure 2.4, left) inhabit the inter-tidal zones along the coast with a high salinity level. Biochemical and molecular mechanisms enable mangroves to cope with salt stress, for example: "*control of ion uptake by roots and transport into leaves*" [Parida & Das 2005], see Figure 2.4 (right).

3 Homeostasis is the ability of a living organism, cell or group to maintain the internal environment within tolerable limits despite the changes in the surrounding environment [Cambridge dictionaries].

Figure 2.4

Left: Mangrove habitat, Costa Rica. Right: the deposition of salt in the form of crystals on older leaves close to falling, courtesy of Peripitus [2006].

2.5.2 Morphological

Morphological adaptation is a structural feature that enhances the adjustment of organisms to their particular environment, and enables better functionality for survival. Various structural features influence organism adaptation, among which are size, form, colour, and pattern. The special form of stem, small and thin leaves, and extensive root system, are a good example for morphological adaptation among desert plants (Figure 2.5). Such stems allow water storage and self-shading situation, small leaves reduce water loss, and the extensive root system enables the plant to collect as much moisture as possible.

Figure 2.5

Morphological variations in cacti. Images courtesy (from left to right): Axsom [2006], Eisenberg [2009], Johansson [2010], Mattdooley40 [2010].

2.5.3 Behavioural

Behavioural adaptation is the actions organisms take for survival. For example, birds migrate, squirrels hibernate, and social insects exhibit swarm behaviour. This type of adaptation is linked to a signal feedback system of signal and response, where behaviour marks an interaction between the organism and its environment. In this context, Piaget [1967] interprets adaptation as "*equilibrium between the action of the organism on the environment and vice versa*". Piaget emphasizes that an action takes place for necessity, "*i.e., if the equilibrium between the environment and the organism is momentarily upset, and action tends to re-establish the equilibrium*" [Piaget 1967]. In order to cope with the new situations that the environment generates, the organism can behave accordingly by reacting to stimuli (from the surrounding environment), create an appropriate response, and execute that response for an optimal result. Various examples can be found in nature for such behaviour. For example, penguins huddle together during snowstorms thereby reducing surface area and decreasing heat loss (Figure 2.6).

Figure 2.6

Left: Penguins huddle together to reduce heat loss, courtesy of *Australian Antarctic Division* [2012]. Right: a group of huddling penguins, which consists of about 2500 males, reproduced from Gilbert *et al.* [2006], with permission from Elsevier.

2.6 Solutions inspired by nature - Biomimetics

Living organisms have unique integration geometries and techniques that allow them to adapt to different environments. Through more than 3.8 billion years, "*living organisms have been perfecting and optimizing their wares without consuming fossil fuel, polluting the planet or risking their future*" [Benyus 1997]. The discipline, in which solutions are obtained by emulating nature's functional analogies, strategies, mechanisms, and processes, is addressed in the current work as *biomimetics*[4]. Biomimetics is equivalent to the German word bionik (or bionic), which was coined by Otto Schmidt in the 1950s [Vincent *et al.* 2006]. Biomimetics is about the transfer of nature's strategies into technology for innovation. Other words may appear as synonyms, e.g. bio-inspired,

4 Biomimetics is derived from the Greek, Bios meaning life, and Mimesis meaning to imitate. Other used terminologies: biomimicry, bio-inspired, bionik, or bionics.

biomimesis, and biomimicry. The later (biomimicry) is used by the Biomimicry Guild, which integrates ecological and sustainable principles in the design process [Biomimicry 3.8].

Biomimetics is not a new idea; humans have been seeking solutions in nature since the existence of humanity. One of the early documented examples of biomimetics is the study of bird flight by Abbas Ibn Firnas (810-887) and later by Leonardo da Vinci (1452-1519), which led to the first controlled airplane in 1903 by the Wright brothers. The field of biomimicry is an emerging field in architecture, where its potential application is being explored and evaluated.

The novel work by Thompson [1942] is considered among the leading works in the field of treating the living organisms as role models for engineering solutions. More detailed, Benyus [1997] sets three major aspects for biomimicry: considering nature as model, measure, and mentor. In architecture, Gruber [2011] explored the overlaps between architecture and biology in order to show potential innovative solutions, and to provide an extensive overview on various approaches.

Biomimetics is growing in the academic discipline, where various approaches are evolving to apply biomimetics in the design process, and result in transformable and responsive adaptation (see Table 2.1). A research study on various biological role models for climate adaptation yielded to a proposal for a visionary permeable wall [Braun 2008]. Several research groups are implementing biomimetics in the education program. For example, the EmTech research group at AA London aims towards biological paradigms for architecture, where they design structures that integrate form and material based on differentiation and emergence principles found in nature [Hensel & Menges 2006]. The designs exhibit dynamic and behavioural adaptation patterns presented through computational environments, and realized into extensive physical models (prototypes) for validation. Another example is the Institute of Building Structures and Structural Design (itke) at the University of Stuttgart that investigates the kinetic and deployable patterns found in nature for possible technological application in buildings [Itke 2011]. Likewise, material science applications are also emerging in research laboratories. Inspired by biological systems in which a surface repels water from surface (among other phenomena), researchers at the Wyss Institute [2011] have developed a super-hydrophobic material that is able to repel water more than other existing surfaces.

In the current work, the biomimetic focus is on the transfer and integration of multiple functional principles and ideas from nature into building envelopes to adapt to changing environmental conditions. This work extends beyond the existing attempts in applying biomimetics in the field of architecture that could be categorized under two specific realms: morphological (form-based mimicry) and service or products for buildings.

2.6.1 Morphology: form and structure

Nature has always inspired architects for forms, structures, and various analogies. Some analogies considered frequently to represent efficient structural performances include bones, trees, and plants (Figure 2.7).

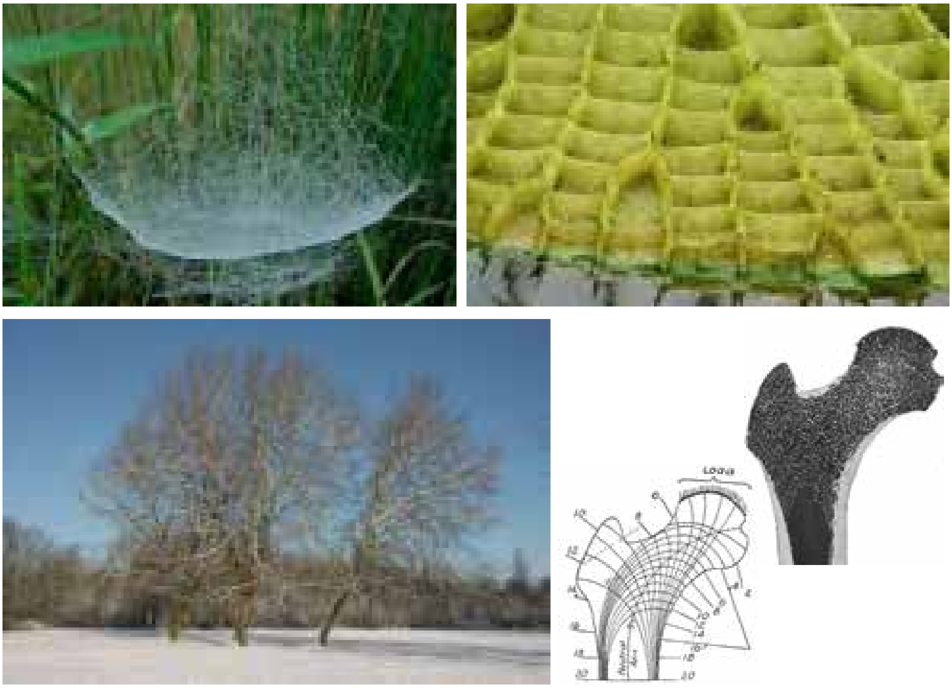


Figure 2.7

Efficient structural performances in nature. Left to right, up to bottom: spider web - reproduced by permission from Lewis Scharpf © 2004 [Scharpf 2004], water Lilly - courtesy of Madebyben [2008], trees, and femur bone - reproduced from Koch [1917]

Several architectural examples from the last two centuries exist for nature inspired designs. Frequently cited examples are listed below:

- **Crystal Palace** by Joseph Paxton (1803–1865) was built in 1851 and erected in Hyde Park, London, to exhibit recent technological advances from the industrial revolution. The construction was inspired by the structural features of the giant Amazon Water Lily, which resulted in great qualities of light and openness by the employment of both cast iron and glass in the construction (Figure 2.8). The construction provided a great inspiration for the design of modern greenhouses.

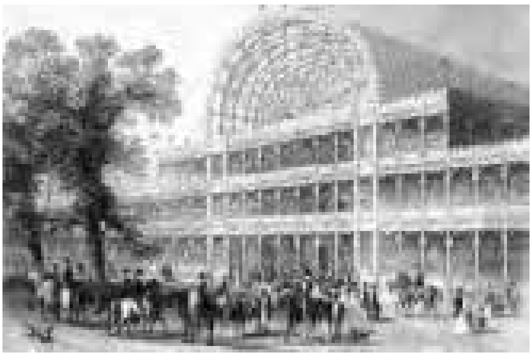


Figure 2.8

The front entrance of the Crystal Palace, Hyde Park, London that housed the Great Exhibition of 1851, the first World's Fair. From [Tallis 1852].

- La Sagrada Familia by Antoni Gaudi (1852–1926) is an unfinished church, which represents organic style and load bearing principles. Gaudi designed among others, columns inspired from pattern of trees (Figure 2.9), honeycomb windows, and stairways inspired by spirals in nature.

Figure 2.9

Ceiling view of la sagrada familia, Barcelona.

- The Geodesic Dome by Buckminster Fuller (1895 –1983) is a spherical or semi-spherical lightweight construction principle (Figure 2.10). The principle was an outcome of the exploration of structural principles in nature for constructions [Sieden 1989].

Figure 2.10

Geodesic dome by Buckminster Fuller, Montreal, Canada. Courtesy of Thévenet [2001].

- The Olympic Stadium (Munich) by Gunther Behnisch (1922-2010) and Frei Otto represents large lightweight tensile structures [Dickson 2000], see Figure 2.11.

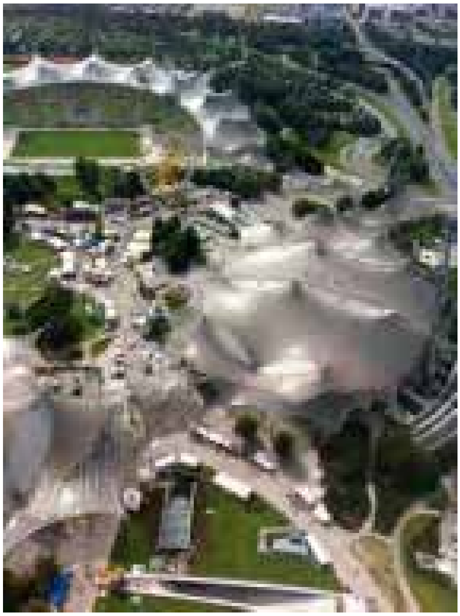


Figure 2.11 ………………………………….
Left: aerial view of the roofing structure above the Olympic stadium in Munich. Courtesy of Tamim Nassar.

- The Eastgate Centre (Harare), by Mick Pearce 1996, is a shopping centre and office block, with a natural and passive ventilation and cooling system. The system is based on principles found in termite mounds (see Figure 2.12) [Turner & Soar 2008].

Figure 2.12 ……………………………………………………………………………….
Eastgate Centre, Harare, Zimbabwe (foreground, the building with the large number of chimneys on top), Michael Pearce. Courtesy of Brazier [2008].

- The Eden Project Biomes (Cornwall) by Nicholas Grimshaw, is a botanical garden inspired by the efficient structural forms of nature [Prance 2002]. The biomes are enclosed in domes that consists of hundreds of inflated EFTE cells attached to hexagonal and pentagonal steel frames (Figure 2.13).

Figure 2.13 ....

Panoramic view of the geodesic dome structures of Eden Project. Courtesy of Matern [2006].

2.6.2 Processes: building systems and services

Several models from nature have been explored and examined to provide solutions for the built environment that influence energy requirements. By emulating specific functional attributes from nature, specific services rather than a solution for the overall building shape and construction, can be found. The following list demonstrates successful examples in this field:

- StoLotusan, developed at Sto Corp. 1999, is a coating inspired by the microstructure of lotus leaves that repels water and keeps them clean [Sto Corp.] (see Figure 2.14 left). This product is used for building facades where it enables cleaning the dirt at every time it rains, and reduces the chances for algae and fungal growth on the facades (see Figure 2.14 right), and significantly reducing energy expenditure in keeping the building clean [Rouni & Kim 2006].

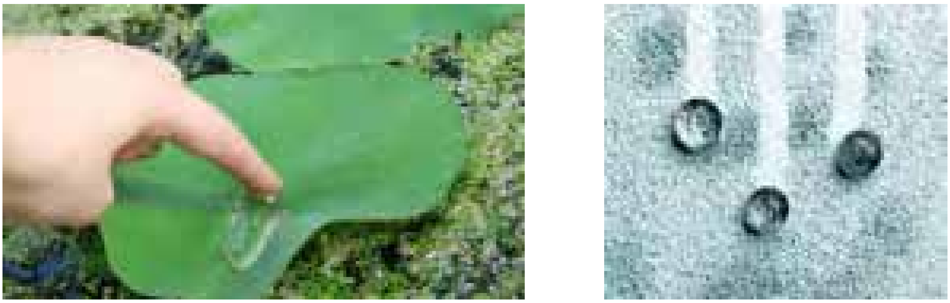


Figure 2.14 ....

Left: water flows off the lotus leaf. Right: StoCoat Lutsan mimics the lotus effect, where water and dirt flow off the facade, courtesy of Sto Corp. [2012].

- Dye-sensitized solar cell (DSSC) is a solar cell generating electricity invented by Michael Grätzel and Brian O'Regan at the École Polytechnique Fédérale de Lausanne in 1991. DSSCs are based on a semiconductor formed between a photo-sensitized anode and an electrolyte inspired by photosynthesis process (e.g. Figure 2.15). DSSCs are considered very efficient, which can then be printed onto building materials such as steel, glass, and plastic allowing them to generate electricity [Bard & Fox 1995].

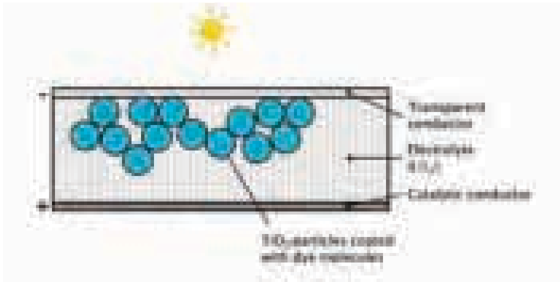


Figure 2.15

Structure of a dye sensitized photovoltaic cell. Courtesy of Maslisko [2008].

- Flectofin ®, designed and developed at ITKE, is a shading device inspired by the mechanics of Strelitzia reginea flower. The Flectofin is a hinge-less louver system that is capable of shifting its fin 90 degrees by inducing bending stresses in the spine caused by displacement of a support or change of temperature in the lamina, Figure 2.16 [Lienhard *et al.* 2011].

Figure 2.16

Left: full scale prototype of the Flectofin ® facade shading system. Right: "*Simulation of the kinetic structure in finite elements showing subsequent deformation of the wing due to bending in the backbone and the corresponding residual stress*." Courtesy of Julian Lienhard, ITKE. [Lienhard *et al.* 2011]

2.7 Conclusions

The design of adaptive building envelopes is required in order to provide comfort state for occupants. An adaptive building envelope has to adapt and manage the changing exterior environmental conditions, as well as the interior demands and activities of the occupants.

Adaptation strategies and principles can be learned from living organisms in nature. Living organisms have developed through their evolution various strategies to cope with the different climatic aspects that suit different environmental conditions. Investigating and analysing these strategies and their dominating principles is essential prior to the transfer of their strategies to adaptive building envelopes. The fact that nature provides a large source of strategies requires a strategic selective design methodology for adaptive building envelopes. Such a methodology is proposed in the next chapter.

References

Addington, M. & Schodek, D.L., [2005]. *Smart Materials and Technologies: for the architecture and design professions*, Burlington, MA: Architectural Press.

ASHRAE, [2004], *Standard 55-2004*: Thermal Environmental Conditions for Human Occupancy, Atlanta.

Australian Antarctic Division – Australian Government, Department of Sustainability, Environment, Water, Population and Communities. Available online at: http://www.antarctica.gov.au/about-antarctica/wildlife/animals/penguins/emperor-penguins/breeding-cycle (retrieved August 2012).

Arthur Ogawa [2009]. *Psychrometric Chart for Sea-level pressure using SI units*, available online at: http://en.wikipedia.org/wiki/File:PsychrometricChart.SeaLevel.SI.svg (retrieved July 2012).

Auliciems, A. [1983] Psychophysical criteria for global thermal zones of building design. *International Journal of Biometeorology*, **27**, pp. 69–86.

Axsom D. [2006]. *Aloe polyphylla in the San Francisco Botanical Garden (formerly Strybing Arboretum)*, available online at: http://commons.wikimedia.org/wiki/File:Succulent_spiral.jpg (retrieved September 2012).

Badarnah, L. & Knaack, U., [2008]a, Organizational features in leaves for application in shading systems for building envelopes, Proc. of *the fourth Design & Nature Conf.: Comparing Design and Nature with Science and Engineering*, Brebbia CA (ed.), Southampton: WITpress, 87-96.

Badarnah, L. & Knaack, U., [2008]b, Shading/energy generating skin inspired from natural systems, Proc. of *SB08: World Sustainable Building Conf.* 2008 305-312.

Badarnah, L., Nachman Farchi, Y., and Knaack, U., [2010]. Solutions from nature for building envelope thermoregulation, Proc. of *the fifth Design & Nature Conf.: Comparing Design and Nature with Science and Engineering*, Carpi A & Brebbia CA (eds.), Southampton: WITpress, 251-262.

Baier, B. & Meyer-Miethke, S. (eds.), [1975]. *IL 14 - Adaptable Architecture*, Stuttgart: Druckerei Heinrich Fink KG.

Banham, R., [1984]. *The Architecture of the Well-tempered Environment*, 2nd ed., London: The Architectural Press Ltd.

Bard, A.J. & Fox, M.A., [1995]. Artificial Photosynthesis: Solar Splitting of Water to Hydrogen and Oxygen. *Accounts of Chemical Research*, **28**(3), pp. 141-145.

Benyus, J.M., [2002]. *Biomimicry: Innovation inspired by nature*, New York: HarperCollins publishers.

Biology-online dictionary, available online at: http://www.biology-online.org (retrieved January 20110.

Bornehag, C.G., Sundell, J., Bonini, S., Custovic, A., Malmberg, P., and Skerfving, S., [2004]. Dampness in buildings as a risk factor for health effects, EUROEXPO: a multidisciplinary review of the literature (1998–2000) on dampness and mite exposure in buildings and health effects, *Indoor Air*, **14**(4), pp. 243–257.

Braun, D.H., [2008]. *Bionisch inspirierte Gebäudehüllen*, PhD dissertation, Stuttgart University, available online at: http://elib.uni-stuttgart.de/opus/volltexte/2008/3614/.

Brazier, D. [2008]. *Eastgate Centre, Harare, Zimbabwe (foreground, the building with the large number of chimneys on top)*. Available online at: http://en.wikipedia.org/wiki/File:Eastgate_Centre,_Harare,_Zimbabwe.jpg (retrieved July 2012).

Cambridge dictionaries, available online at: http://dictionary.cambridge.org (retrieved January 2011)

Compagno, A., [2002]. *Intelligent Glass Facades: Materials, Practice, Design*, 5th ed. , Berlin: Birkhauser.

Davies, M., [1981]. A wall for all seasons, *RIBA Journal*, **88**(2).

Del Grosso, A.E. & Basso, P., [2010]. Adaptive building skin structures, *Smart Materials and Structures*, **19**(124011).

Dickson, M., [2000]. On Frei Otto's philosophy of widespan lightweight structures. In *Widespan: roof structures*, M. Barnes & M. Dickson eds., London: Thomas Telford Publishing, pp. 19-40.

Eisenberg P.J. [2009]. *Cleistocactus sepium (syn' Borzicactus websterianus) and other tall cacti, Huntington Library Desert Botanical Garden in afternoon after and during rain, February 2009 - Various cactus and succulent plants*, available online at: http://commons.wikimedia.org/wiki/File:Borzicactus_Websteramus,_Cleistocactus,_Huntington_Desert_Garden.jpg (retrieved September 2012).

Fang, L., Clausen, G., and Fanger, P.O., [1998]. The impact of temperature and humidity on perception of indoor air quality, *Indoor Air*, **8**(2), pp. 80–90.

Fanger, P.O., [1972]. *Thermal Comfort, Analysis and Applications in Environmental Engineering*, New York: McGraw-Hill.

Gao, Y., Wang, S., Kang, L., Chen, Z., Du, J., Liu, X., Luo, H., and Kanehira, M. [2012]. VO2-Sb:SnO2 composite thermochromic smart glass foil. *Energy & Environmental Science*, **5**(8), pp. 8234-8237.

Gilbert, C., Robertson, G., Le Maho, Y., Naito, Y., and Ancel, A., [2006]. Huddling behavior in emperor penguins: Dynamics of huddling, *Physiology & Behavior*, **88**, pp. 479-488.

Gosztonyi, S., Brychta, M., and Gruber, P., [2010]. Challenging the engineering view: comparative analysis of technological and biological functions targeting energy efficient facade systems, Proc. of *Int. Conference Design & Nature V: comparing design in nature with science and engineering*, C. Brebbia & A. Carpi eds., Southampton: WIT press, pp. 491-502.

Gregory, D.P., [1986]. *Adaptive building envelopes*, Building Services Research and Information Association, Technical Note TN3/86, Berkshire: BSRIA.

Gruber, P., [2008]. The signs of life in architecture, *Bioinspiration & Biomimetics* 3:023001(9p).

Gruber, P., [2011]. *Biomimetics in Architecture: Architecture of Life and Buildings*, Vienna: Springer.

Hensel, M. & Menges, A. (eds.), [2006]. *MORPHO-ECOLOGIES*, London: AA Publications.

Hill, R.W., Wyse, G.A., and Andreson, M., [2008]. *Animal Physiology*, Massachusetts: Sinauer Associates Inc.

Hosale, M.D. & Kievid, C., [2009]. InteractiveWall – a prototype for an emotive architectural component, in *iA: No. 3*, Oosterhuis K., Xia X., and Slootweg O. (eds.), Rotterdam: Episode Publishers, pp.70-83.

Itke - Institute of Building Structures and Structural Design, University of Stuttgart, available online at: http://www.itke.uni-stuttgart.de/forschung.php?id=61 (retrieved October 2011).

Johansson C.T. [2010]. *Okänd kaktus*, available online at: http://commons.wikimedia.org/wiki/File:2811_cactus.jpg (retrieved September 2012).

Koch, J.C. [1917]. The Laws of Bone Architecture. *Am. Jour. of Anat.*, **21**, pp. 177-298.

Kronenburg, R. & Klassen, F. (eds.), [2006]. *Transportable environments 3*, New York: Taylor & Francis.

Lechner, N. [2009]. *Heating, Cooling, Lighting: sustainable design methods for architects*, 3rd ed., New Jersey: John Wiley & Sons, Inc.

Lelieveld, C.M.J.L., Voorbij, A.I.M., and Poelman, W.A., [2007]. Adaptable Architecture, Proc. of *Int. Conference Building Stock Activation*, Tokyo: TAIHEI Printing Co., Ltd..

Lelieveld, C.M.J.L. & Voorbij, A.I.M., [2009]. Adaptable Architecture with the Application of Dynamic Materials. In *Lifecycle Design of Buildings, Systems and Materials*, E. Durmisevic, ed., Enschede, The Netherlands

Le Corbusier, [1991], Edith Schreiber Aujame, trans. (1930 in French). *Precisions on the present state of architecture and city planning*, Cambridge: MIT Press, pp: 62-66.

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., and Knippers, J., [2011]. Flectofin: a nature based hinge-less flapping mechanism. *Bioinspiration & Biomimetics, **6**,* special issue on Biomimetics of Movement, 045001.

Linden, A.C. van der, Boerstra, A.C., Raue, A.K., Kurvers, S.R., and Dear, R.J. de, [2006]. Adaptive temperature limits: A new guideline in The Netherlands A new approach for the assessment of building performance with respect to thermal indoor climate, *Energy and Buildings*, 38. pp. 8-17.

Louw, G.N. & Seely, M.K., [1982], *Ecology of Desert Organisms*, London: Longman Group Ltd.

Madebyben [2008]. *The underside of a giant water lilly leaf*, available online at: http://www.flickr.com/photos/madebyben/1239786533/in/photostream/ (retrieved September 2012).

Marten, J. [2006]. *Panoramic view of the geodesic dome structures of the Eden Project*, available online at: http://en.wikipedia.org/wiki/File:Eden_Project_geodesic_domes_panorama.jpg (retrieved July 2012).

Maslisko [2008]. *Structure of a dye sensitized photovoltaic cell*, available online at: http://commons.wikimedia.org/w/index.php?title=File:Dye_sensitized_cell_principle.svg&page=1 (retrieved September 2012).

Mattdooley40 [2010]. *Dew on cactus spines*, available online at: http://www.flickr.com/photos/59893103@N05/5491570029/in/photostream (retrieved September 2012).

Nicol, J.F & Humphreys, M.A. [2002] Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34, pp. 563-572.

Parida, A.K. & Das, A.B., [2005]. Salt tolerance and salinity effects on plants: a review. *Ecotoxicology and Environmental Safety*, **60**, pp. 324-349.

Peripitus [2006]. Photo taken on the mangrove walk St Kilda, South Australia, available online at: http://en.wikipedia.org/wiki/File:Saltcrystals_on_avicennia_marina_var_resinifera_leaves.JPG (retrieved July 2012).

Piaget, J., [1967], (1947 in French). *The Psychology of intelligence*, Piercy M. trans., London: Routledge & Kegan Paul Limited.

Prance, G.T., [2002]. A paradise for economic botanists: The Eden project. *Economic Botany*, **56**(3), pp. 226-230.

Rosen, D.A.S. & Renouf, D., [1997]. Seasonal changes in blubber distribution in atlantic harbor eals: indication of thermodynamic considerations. *Marine Mammal Science*, **13**(2), pp. 229-240.

Rouni, G.K. & Kirn, M., [2006]. Modern construction materials & environment quality of buildings. International Workshop on Energy Performance and Environmental Quality of Buildings, Milos island, Greece.

Schmidt-Nielsen, K., [2007], *Animal physiology: adaptation and environment*, New York: Cambridge University Press.

Scharpf, L. [2004]. *Bowl and Doily Spider Web*, available online at: http://www.pbase.com/lejun/image/34104728&exif=N (retrieved September 2012).

Sieden, L.S., [1989], The birth of the geodesic dome; how Bucky did it. (R. Buckminster Fuller). *The Futurist*, 23(6), pp. 14.

Sto Corp., available online at: http://www.stocorp.com/index.php/component/option,com_catalog2/Itemid,196/catID,43/catLevel,5/lang,en/productID,34/subCatID,44/subCatIDBP,44/subCatIDnext,0/ (retrieved January 2012).

Sterk, d'E., [2003]. Using Actuated Tensegrity Structures to Produce a Responsive Architecture. In Proceedings of *the 2003 Annual Conference of the Association for Computer Aided Design In Architecture*, Indianapolis, IN, USA, pp. 85–93.

Sunwoo, Y., Chou, C., Takeshita, J., Murakami, M., and Tochihara, Y., [2006]. Physiological and subjective responses to low relative humidity in young and elderly men, *Journal of Physiological Anthropology*, **25**(3), pp. 229–238.

Tallis, J. [1852]. *Tallis' History and Criticism of the Crystal Palace*. Photo available online at: http://en.wikipedia.org/wiki/File:Crystal_Palace.PNG (retrieved July 2012).

Thévenet, C. [2001]. *Terre des Hommes, Île Sainte-Hélène, Montréal, Québec, Canada*. Available online at: http://en.wikipedia.org/wiki/File:Biosph%C3%A8re_Montr%C3%A9al.jpg (retrieved August 2012).

Thompson, D.W. (D'Arcy Wentworth), [1942]. *On Growth and Form*, Cambridge: Cambridge University Press.

Turner, S. & Soar, R.C., [2008]. Beyond biomimicry: What termites can tell us about realizing the living building. *Proceedings of the first international conference on Industrialised, integrated, intelligent sustainable construction* (I3CON), Loughborough, UK. Hassan T. & Ye J. (eds.), pp. 221–237.

UNESCO, World Heritage Convention, available online at: http://whc.unesco.org/en/list/965/ (retrieved 2011).

Vargas, P.A., Moioli, R.C., von Zuben, F.J., and Husbands, P., [2009]. Homeostasis and evolution together dealing with novelties and managing disruptions. *International Journal of Intelligent Computing and Cybernetics*, **2**(3), pp. 435-454.

Vincent, J.F.V., Bogatyrev, O.A., Bogatyreva, N.R., Bowyer, A., and Pahl, A.K., [2006]. Biomimetics – its practice and theory. *Journal of the Royal Society Interface*, **3**, pp. 471-482.

Wadhawan, V.K., [2007]. *Smart Structures: blurring the distinction between the living and the non living*, New York: Oxford University Press.

Watson, D., [1997]. Architecture, Technology, and Environment. *Journal of Architectural Education*, **51**(2), pp. 119-126.

Wigginton, M., & Harris, J., [2002]. *Intelligent Skins*, Oxford: Butterworth-Heinemann.

Wyss Institute, available online at: http://wyss.harvard.edu (retrieved October 2011)

Design methodology

Chapter 3

3.1 Introduction

Nature provides a large database of adaptation strategies that can be implemented in biomimetic designs, in general, and in the design of adaptive building envelopes, in particular. Morphology and form are most common traits to be copied from natural systems into architecture. However, these traits seldom match the function these systems represent in nature, and therefore not truly representing a successful biomimetic design. Additionally, successful concept designs are limited, likely due to a number of factors beyond the ability to emulate nature's strategies to meet corresponding functional needs. Challenges in implementing biomimetics likely also include: (1) the search for, and the selection of, an appropriate strategy or multiple strategies from the large database provided by nature; (2) scaling difficulties – strategies that work at one scale (e.g. nano) might not work at another (e.g. micro); and (3) conflicts between solutions of integrated parts of the concept design.

The selection of role models from nature is a common challenge facing architects. Processes, morphologies, and systems are all strategies available for mimicking, which can be implemented at various scales of results, e.g. material, object/product/element, building, and urban. From the literature, two main approaches with various terminologies are noticed in biomimetics:

- *Biology to design* [Baumeister 2012], *bottom-up* [Speck *et al.* 2006], *biomimetics by induction* [Gebeshuber & Drack 2008], and *solution-based* [Vattam *et al.* 2007], are inspired by an observation in nature which leads to a technological design, e.g. the Velcro fastener inspired by the hook & loop mechanism in the burdock seeds. This approach is referenced, in the current work, as *solution-based*.

- *Challenge to biology* [Baumeister 2012], *top-down* [Speck *et al.* 2006], *biomimetics by analogy* [Gebeshuber & Drack 2008], and *problem-based* [Vattam *et al.* 2009], seek a solution from nature for a particular engineering problem, e.g. how to reduce drag on swimsuits? Answer from biology: sharkskin pattern/morphology. This approach is referenced, in the current work, as *problem-based*.

The current work follows the *problem-based* approach where solutions from nature are sought to solve particular building envelope adaptation requirements, e.g. thermoregulation in arid areas. This approach is taken to address the myriad challenges associated with adaptive building envelopes.

In this chapter, a novel structured strategy for design concept generation of adaptive building envelopes is presented. The design methodology selects dominant strategies that function simultaneously in nature. The proposed strategy consists of several phases and sub-phases, which are presented in unique flow charts, tables, and figures that provide a selective user-friendly tool, which leads to a concept design of the living envelope.

3.2 Biomimetic design strategies

Several active groups have developed strategies for design concept generation inspired from nature. Selected groups are presented in this section for comparison and evaluation. A summary of their strategic steps are compared in section 3.2.1, and their analyses are presented in section 3.2.2.

Biomimicry 3.8 [Biomimicry 3.8 2011]. The inspiring book of Benyus [2002], *Biomimicry: innovation inspired by nature* (first published in 1997), has been considered as an influential work in various disciplines for sustainability. In 1998, Benyus and Baumeister founded the Biomimicry Guild to consult organisations on how to use biological phenomena to inspire problem solving. In 2008, they launched an online resource database of nature's solutions, called AskNature.org. Recently (September 2011), Biomimicry 3.8 was announced to host the various biomimetic activities, and include: Biomimicry book (1997), Biomimicry Guild (1998), Biomimicry Institute (2006), AskNature (2008) and Biomimicry Professional Pathways (2010). AskNature (2010 Earth Award) provides an online public platform for interdisciplinary collaboration and inspiration by the various principles found in nature for numerous functions and challenges. Currently (July 2012), AskNature contains over 1,500 natural strategies categorized by function (representing 164 different functions). The AskNature strategy [AskNature 2011] approaches the design challenge by identifying functions – i.e. don't ask: "*what do I want to design*?", but rather ask: "*what do I want my design to achieve*?", provides a Biomimicry Taxonomy to organize how organisms meet different challenges, provides a step by step examples how to use and browse the online database, and relies on verbs and their synonyms to be used in their search engine. The steps applied in the design process and taught by Biomimicry 3.8 are presented in Figure 3.1. Additionally, the strategy involves validation against Life's Principles, which results in sustainable solutions.

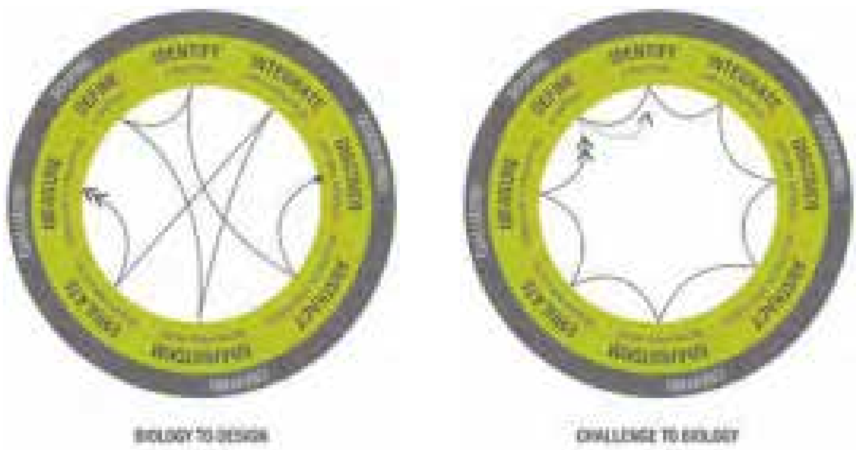


Figure 3.1

Biomimicry spiral - design tools, © Biomimicry 3.8 [Baumeister 2012]. Provided with permission by © Biomimicry 3.8.

BioTriz is a project to extend the original TRIZ with biological data [Vincent *et al.* 2006]. TRIZ is a theory of inventive problem solving developed by Genrich Altshuller in 1946 based on patent database analysing [Lerner 1991]. The BioTriz is a problem-solving method via a database of biological data of functions, effects, and contradictions, to make biological information available for engineers [Bogatyreva *et al.* 2002, Bogatyreva *et al.* 2003]. The database consists of some 500 biological phenomena, with over 270 functions, and 2500 conflicts, which are stored by different levels of complexity – BioTriz matrix [Vincent *et al.* 2006]. By defining a problem, the BioTriz matrix will result in various inventive principles to be applied in the solution development. Craige *et al.* [2008] reported on the potential results of BioTriz, and present insulation solution for buildings against short-waves radiation during the day and allow long-wave radiation to escape at night [Craig *et al.* 2008]. However, Vincent [2009] describes the process to be out of biological context: "*This solution to the problem does not (as far as the present author knows) actually exist in the natural world; it has no natural prototype. Thus a novel solution has been achieved using the general design strategies that exist in nature, but in the absence of a specific model. It is no longer necessary to know biology in order to benefit from biomimetics!*"[Vincent 2009]. The BioTriz project has since been discontinued and the database is not available online anymore.

L.H. Shu - Mechanical & Industrial Engineering, University of Toronto. Shu conducts research on the creativity in conceptual design, and on the systematic identification and application of biological analogies in biomimetic design [Shu 2011]. Vakili & Shu [2001] describe efforts towards generalizing biomimetic concept generation for the process of design engineering. Biological phenomena are presented at hierarchies of forms, behaviours, and principles for potential analogies [Mak & Shu 2004]. The natural-language approach is used for identifying and applying biological analogies in the design process [Shu 2010]. Chiu & Shu [2007] use the index of biological textbooks and journals to search for bridge verbs (verbs used in biological and engineering domains), which lead to relevant biological phenomena.

Ashok K. Goel - Design & Intelligence Lab, School of Interactive Computing & the Center for Biologically Inspired Design, Georgia Institute of Technology. Goel conducts research, among others, to develop interactive tools for creativity. One of the projects explores analogical reasoning in biologically inspired design [Goel 2011]. Helms *et al.* [2009] adapted the two approaches for biologically inspired design (mainly adapted from Biomimicry 3.8), as presented in Tables 3.1 and 3.2 (Goel column), and observed the design process aiming to understand the various motivations of the design process for the aim of effective strategies development for biologically inspired designs. As an initial attempt, Vattam *et al.* [2010] have developed an interactive knowledge base design environment, called DANE - Design by Analogy to Nature Engine [DANE 2011]. DANE analyses the biological systems under the Structure-Behaviour-Function (SBF) schema [Goel *et al.* 2009].

Thomas Speck - Plant Biomechanics Group (PBG), the Botanic Garden of the University of Freiburg. The PBG is lead by Prof. Thomas Speck, who conducts research on biological systems for possible abstraction to develop technological prototypes.

The group investigates biomechanics, functional, and morphological aspects in plants [PBG]. The group conducts extensive screening of biological organisms to identify role models for potential solving of particular technical problems. Structural and functional principles are distinguished, and the role models are analysed quantitatively. They use various methods including: biomechanical tests, and different light and electro-optical analyses [Masselter *et al.* 2010]. After that, the structural principles are modelled and manufactured as prototypes for validation and finally introduced to the market. Several successful results were reported in the development of new technical solutions, for example, for light-weight structures and self-repairing materials [Milwich *et al.* 2006].

3.2.1 Comparison of the strategies

The presented biomimetic design strategies have differences in particular in phase details. Differences between the design strategies, when addressing the two approaches, *problem-based* and *solution-based*, are summarized in Table 3.1 and Table 3.2, respectively.

In the problem-based approach (Table 3.1) all methodologies have a similar initial phase – problem definition, where a minor difference is noticed at Biomimicry 3.8 by including Life's Principles as aspirational goals at the scoping phase. At the Exploration & Investigation phase, all methodologies aim to discover a biological model or analogy,

Challenge to Biology (*problem-based*). The steps adapted by the investigated biomimetic methodologies. Categorized based on the three general phases of the design process: *problem definition*, *exploration & investigation*, and *solution development*.

Table 3.1

	Biomimicry 3.8	***BioTRIZ***	***Shu***	***Goel***	***PBG***
Problem definition	Identify function Define Context Integrate Life's Principles into design brief	Define problem Analyze & understand problem	Problem definition	Problem definition Reframe problem	Formulate the technical problem
Exploration & Investigation	Discover natural models Abstract biological strategies into design principles	Find functional analogy in biology Compare solution from biology and from TRIZ	Search for biological analogies Assessing biological analogies	Biological solution search Define the biological solution Principle extraction	Seek for analogies in biology Identify corresponding principles Abstract from the biological model
Solution development	Brainstorm bio-inspired ideas Emulate design principles Measure using Life's Principles	List principles from both biological and technical domains Develop idea	Applying biological analogies	Principle application	Implement technology through prototyping and testing

though some proceed with abstracting design principles (e.g Biomimicry 3.8, Shu, and PBG). However, the methodologies have different involvement in the Solution development phase: Biomimicry 3.8 incorporates Life's Principles in the validation of the design concept for sustainability, BioTriz provides a set of principles from biological and technical domains but it is not involved in solution development, Shu provides the biological analogies, Goel applies the principles for solution development, and PBG proceeds to prototype and carries physical tests as solution proof.

In the solution-based approach (Table 3.2), the various steps were categorized under the biological domain and technological domain, where some steps are identified as a transfer phase between the two domains. The presented methodologies have similar steps in the technological domain (solution-based) and solution development phase (problem-based).

Despite the difference in the initial phase between the two approaches (problem-based & solution-based), the methodologies show a similar trend in the transfer from biological domain to technological domain. However, a major difference lies in the way the different approach the various phases of the biomimetic process. Further elaboration is presented in the next section.

Biology to Design (*solution-based*). The steps adapted by the investigated biomimetic methodologies. Categorized by *biological* and *technological* domains and the *transfer* phase between the domains.

Table 3.2

	Biomimicry 3.8	***Goel***	***PBG***
Biological domain	Discover natural models	Biological solution identification Define the biological solution Principle extraction	Identify a biological system Analyze biomechanics, functional morphology, and anatomy Understand the principles
Transfer phase	Abstract biological strategies into design principles Identify function and define context Brainstorm bio-inspired ideas	Reframe the solution	Abstract from the biological model
Technological domain	Integrate Life's Principles Emulate design principles Measure using Life's Principles	Problem search Problem definition Principle application	Implement technology through prototyping and testing

3.2.2 Analyses of problem-based strategies

The presented strategies for biomimetic concept generation involve three domains in the biomimetic process. The problem-based approach is divided into three general domains: problem, nature, and solution (Table 3.3). Two general transitions (Transitions 1 & 2) and four sub-transitions (transitions 1.1, 1.2, 2.1, & 2.2) are identified, as presented in Table 3.3. The identified general phases are considered to promote the transitions between the general domains by means of sub-transitions. The sub-phases are the specific steps carried out by some methodologies throughout the biomimetic process.

General layout of a biomimetic process and the applied strategies.

Table 3.3

General domains	General phases	Sub-phases
Problem domain	***Challenge***	**Definition** **Define problem:** BioT, Shu, Goel, PBG **Identify Function and Define Context**: B3.8
Transition 1	*transition 1.1*	**Abstraction** **Identify verbs**: Shu ***Biologize* function**: B3.8 **Conflicts**: BioTriz
	Function	
Nature domain	*transition 1.2*	**Exploration & Investigation** **Search biological key-word set**: Shu **AskNature** (online platform) and Biological Lenses: B3.8 **Database**: BioT **Dane**: Goel
	Analogy	
Transition 2	*transition 2.1*	**Classification** **Categories of similarities**: Gruber **SBF schema** : Goel **Taxonomy**: B3.8
	Abstraction	**Principle identification** **Principle extraction**: B3.8, Shu
Solution domain	*transition 2.2*	**Design concept** **Brainstorm**: B3.8, Goel **Model structural principles**: PBG
	Emulation	**Emulate principles** B3.8, Shu **Evaluation** **Life's principles:** B3.8 **Prototype test:** PBG

B3.8	Biomimicry 3.8
BioT	Vincent *et al.* 2006
Shu	Vakili & Shu 2001
Goel	Goel *et al.* 2009
PBG	Plant Biomimetics Group
Gruber	Gruber 2011

The main differences between the presented methodologies are relatively minor, but include the means by which they accomplish each sub-phase. The initial phase, Challenge, is common among the analysed methodologies in order to extract functions, which are considered essential to search for the biological analogy. In order to step from the Challenge phase to the Function phase a sub-transition (1.1) is identified, which is performed by means of Abstraction. Three suggestions exist for abstraction: identify verbs (functions are represented by verbs) (Shu), reframe or biologize the question e.g. "*How would nature …*" (B3.8), or formulate a conflict (BioTriz).

Another sub-transition (1.2) is identified between the phases Function and Analogy. The sub-transition 1.2 is carried out mainly by means of exploration and discovering. Shu *et al.* suggest biological textbooks index-based search, and B3.8, BioT, and Goel rely on database search engines, where they have built their own platforms: AskNature.org, BioTriz, and DANE, respectively. B3.8 also recommends an array of "*biological lenses*" for searching existing literature, as well as asking biologists directly.

As the analogy is obtained, further transition is required to assess the abstraction by means of principles identification. This transition (2.1) is the assessment of the biological information that represents the obtained analogy. Goel *et al.* [2009] analyse the information under the structure-behaviour-function schema, and Biomimicry 3.8 classifies the information under the biomimicry taxonomy and the function-oriented database [Baumeister 2012].

The identified principles are applied for concept generation (Emulation phase), and further validation is carried out at different involvement. Biomimicry 3.8 evaluate against Life's Principles to result in a sustainable solution, while PBG build prototypes and carry out simulations and physical tests. Despite the detailed descriptions about some sub-phases and sub-transitions, limited description is available for the sub-transition 2.2 (design concept). Two methods were observed to generate a design concept: (1) by brainstorming several ideas, which might result in several ideas and further filtering is essential (e.g. B 3.8), and (2) by modelling a particular structural principle, which is relevant for a specific organism (e.g. PBG).

3.2.3 Concluding remarks

Although several biomimetic strategies are available, the research on biomimetics as a design tool in architecture is still challenging due to current limitations of systematic design tools which identify relevant biological analogies and abstract the relevant main principles to be applied in concept generation.

In order to find design solutions from nature, the requirements of the artificial system should be defined, and then analogical systems in nature that perform similar functions should be identified. The design tools should support the transitions between the domains, especially the identification of biological analogies and their abstraction for design concept generation. The classification and categorization of aspects from nature based on analogue/similar aspects in architecture (e.g. surface, material, and structure) could assist the design generation [Gruber *et al.* 2011].

The main concerns in the current strategies are the broad range of possibilities and the difficulties in the representation of the biological knowledge for architects/engineers who have limited biological background. For example, Vakili & Shu [2001] describe an approach that facilitates the search process while seeking a wide range of possible analogies. However, this may result in several irrelevant analogies for the design challenge, which will require more efforts to eliminate them. Note that the current thesis directly excerpts some parts of the presented biology in order to avoid misinterpretations.

A new biomimetic design methodology, that generates concept designs for adaptive building envelope, is proposed in the following sections to facilitate the transitions between the various phases of the design process, with a special attention to biological information representation, principles identification and abstraction, and their systematic selection.

3.3 The living envelope methodology

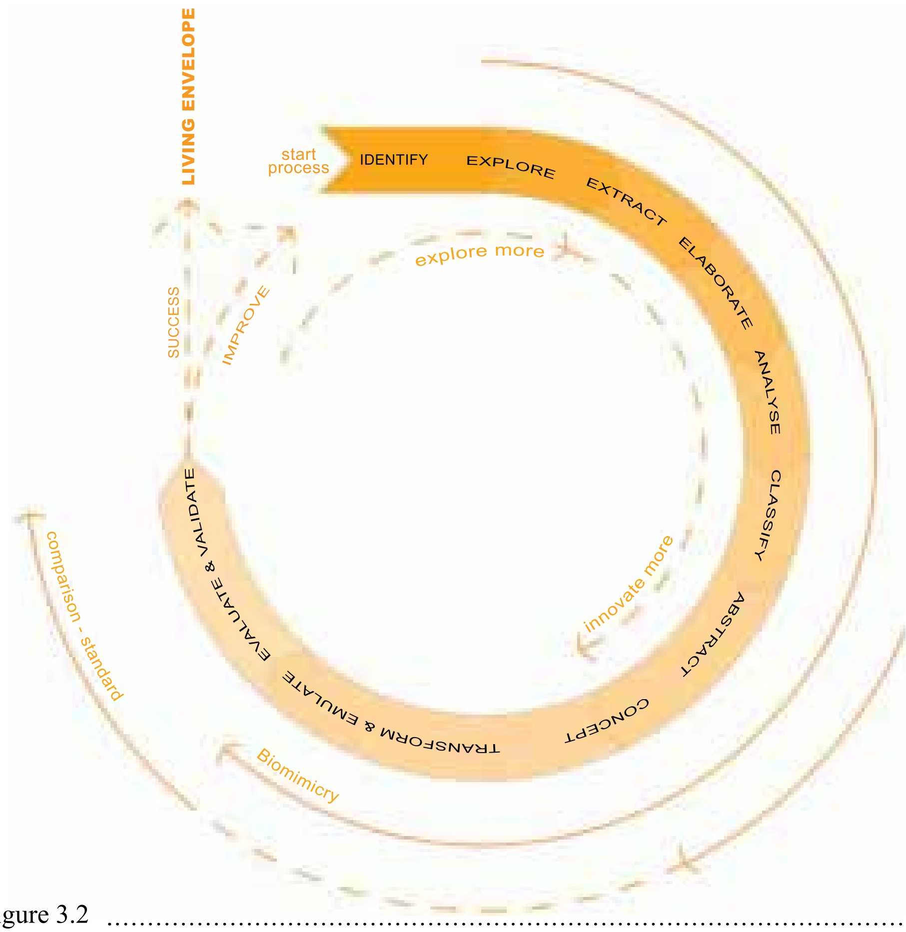


Figure 3.2 Flow chart of the design methodology presenting the various phases to be addressed in order to design the *living envelope*.

The design methodology was set based on two major phases: the preliminary design phase and the emulation phase. Based on results obtained from design workshops carried throughout the research [Badarnah *et al.* 2008, Badarnah 2009], the difficulty of architects to investigate nature's strategies and extract their main principles to establish a design concept was noticed. The transformation of strategies available in nature into technical solutions for building envelopes is a complicated multidisciplinary process. It becomes even more complicated, and often conflicts arise, when integrating a number of strategies from different organisms to achieve improved solutions [Badarnah *et al.* 2010]. Thus, an extended methodology was aimed for the preliminary design phase. This phase is basically dealing with the exploration process and organisms' investigation, and results in leading the architect to a concept design. The emulation phase was out of the scope of current research, as architects are more familiar with this phase, since it is based on a conventional strategy and standard codes.

In order to develop a living envelope, a number of phases has to be carried out: identify the required challenges, explore nature for similar functions, extract & abstract the main principles, build taxonomies, obtain brainstorm ideas, evaluate the ideas, transform the best ideas into designs, build physical models, evaluate and validate them, and determine whether there is a sufficient improvement (success) or further improvement is needed (start again). A flow chart of the various phases of the methodology is illustrated in Figure 3.2, and the corresponding detailed actions are elaborated in Figure 3.4.

3.4 Exploration model

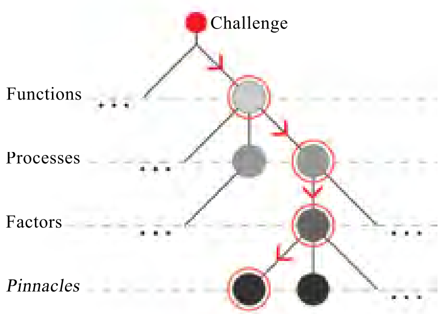


Figure 3.3

Exploration model. Four hierarchical levels map the different entities and their connections.

The exploration model maps the obtained biological information for each challenge at four hierarchical levels (see Figure 3.3). Instead of categorizing first by the biological entities, the current work aims in creating an exploration model that maps functional aspects at the first level, relevant processes at the second level, and influencing factors at the third level. In this model, the biological entities (*pinnacles*[1]) are presented at the fourth level, and represent an example for specific function, process, and factor. This hierarchical model is similar to the Biomimicry Taxonomy (B3.8) which maps master function, sub-functions, and influential factors (context). Within AskNature, using this hierarchy allows one to browse to the representative organism or system [Baumeister 2012].

The search for the biophysical information involves several resources: (1) Books – Animal physiology, with focus on adaptation and environment to provide the basic background [e.g. Schmidt-Nielsen 2007, Hill *et al.* 2008]. Physical principles, with focus on moving fluids [e.g. Vogel 1989]. (2) Scientific articles – provide further elaboration on specific principles and their functional presence in particular organisms or systems. (3) Online databases – relevant keywords provide more focused results [e.g. AskNature.org]. (4) Biologists – directly asking biologists might lead to potential biological analogies [e.g. Baumeister D].

The categorization and organization of the obtained biophysical information is a challenging process, where boundaries are set and a systematic approach is sought. First, the number of levels was limited to four. Second, the entities of each level varies, but fixed for the Functions level. This fixation is important to increase efficiency of the initial design process. The classification of the biological information based on the functional aspects is a favourable approach for transformation in biomimetics, as the hypothesis suggests that constructions and structures in nature have a functional reason, which is the main aspect to establish a suitable analogy [Gruber 2011]. The different entities are connected to each other based on their association. The current thesis presents four basic exploration models for regulation of: Air, Heat, Water, and Light, in chapters 4, 5, 6, and 7 respectively. It is worth noting that the long-term objective is to provide an extensively large database applied in a unified exploration model. The exploration models of chapters 4, 5, 6, and 7 where extended above the selected pinnacles (implemented in the design concept generation) in order to illustrate the selection of pinnacles from a wider database.

3.5 Design concept generation

This section elaborates on the preliminary design phase (Figure 3.4c), and presents the strategies for concept generation (Figure 3.4d). The preliminary design phase is divided into three sub-phases (see Figure 3.4): a general exploration phase (exploration model), pinnacle analysing and abstraction phase, and the determination phase of the features for the design concept (design path matrix). A number of selected organisms or systems, referred to as pinnacles, are investigated. These pinnacles are organisms considered among scientists as having special adaptation strategies, which are provided to demonstrate the extraction of their strategies.

1 Literarily a pinnacle is the summit. Current work defines *pinnacle* as a representative organism or system from nature for a particular adaptation strategy.

Preliminary design phase

Identify phase

Identify the functions of a certain challenge, e.g. heat gain, water gain, and air exchange. Identify environmental context and user's requirements.

Explore & Investigate phase

Explore biological challenges similar to the identified technical challenges. Distinguish the functions and relevant processes in nature, and determine their influential factors and representative *pinnacles*.

Discover & Extract phase

Select relevant processes and pinnacles that correspond with the identified challenge.

Elaborate & Analyse phase

Investigate and analyse the selected pinnacles.

Classify phase

Identify relevant categories to summarize the features for each pinnacle from the various challenges.

Abstract phase

Seek dominant features.

Concept phase

Develop design concepts based on the optimal features from the dominant path of the matrix.

Emulation phase

Transform & Evaluate

Develop the concepts into technical solutions. Apply computer simulations to determine the performance characteristics, and find the optimal set up for the design.

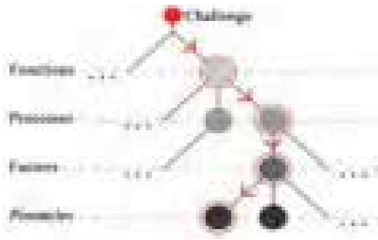
Prototype & Validate

Build a scale physical model of the technical solution, and explore advanced technologies to be applied. Apply physical tests to check the performance of the designs in comparison to standard systems, and ask expert opinions for further validation.

a.

b.

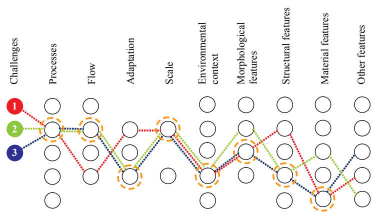
Exploration model (see Figure 3.3)
Build a functional representation of the biophysical knowledge based on hierarchies, or use an existing model relevant to the challenge.



Pinnacle analysis (see Figure 3.7)
Identify strategy, emphasize mechanism, extract main principle, and indicate main feature.

Pinnacle analysing matrix (see Table 3.5)
Build matrix of the various features of the investigated pinnacles, and distinguish the dominant features (*imaginary pinnacles*).

Design path matrix (see Figure 3.9)
Apply the *imaginary pinnacles* in the design path matrix, and distinguish the dominant characteristics and relationships for the optimal design outline.



c. **d.**

Figure 3.4

Design methodology map outline. (a.) The living envelope methodology. (b.) Phases of *preliminary design phase* and *emulation phase* (c. & d.) The preliminary design phase is assisted by the design tools: *exploration model, pinnacle analysis*, *pinnacle analysing matrix*, and *design path matrix*.

3.5.1 Definition of design challenges

Several key functions were identified for the challenges of the building envelope in terms of air, heat, water, and light. These functions are summarized in Figure 3.5, and elaborated in the succeeding chapters 4, 5, 6, and 7, respectively, and their integration is discussed in chapter 8.

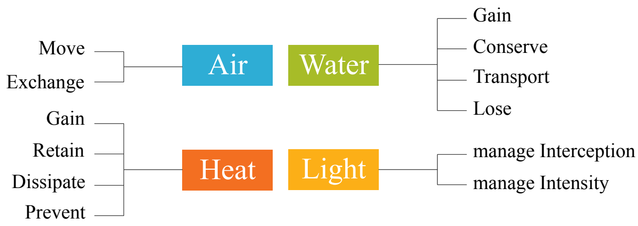


Figure 3.5

The proposed key **functions**.

3.5.2 Identification of exemplary pinnacles

Once the design challenge is defined, the exploration model provides several paths that lead to relevant pinnacles. The defined challenge determines specific functions, and the detail level of definition may as well determine further levels of the exploration model (i.e., processes). Therefore, a specific path is identified (see highlighted continuous path leading to zones a and b in Figure 3.6). On the other hand, the architect has the freedom to choose related factors and pinnacles at the descending levels of the exploration model (see dashed path leading to zones c and d in Figure 3.6).

The defined challenge and degree of freedom in selecting factors and pinnacles have important consequences on the generated design concept, which provides a three-step filtering of the pinnacles: (1) the defined challenge "eliminates" the overwhelming majority of irrelevant pinnacles in the exploration model, and thus increases the efficiency of selecting suitable pinnacles; (2) the degree of freedom in selecting the factors is

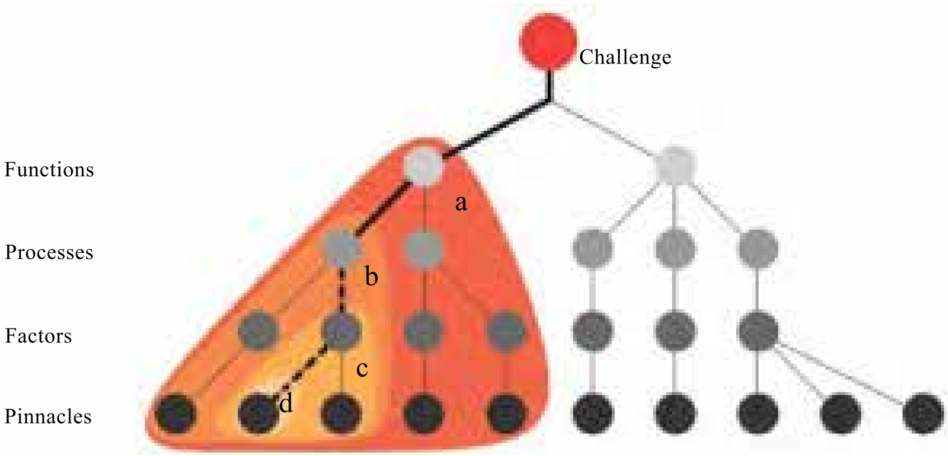


Figure 3.6

Pinnacle identification. By navigating through the exploration model, a path of functions, processes, factors, and pinnacles is distinguished through zoning.

important for optimization of the design in terms of feasibility and preferred technology to be used; and (3) the final selection of pinnacles influences the architectural aspects of the generated design.

The number of pinnacles required in order to obtain a concept design depends on the required challenges and the corresponding strategies of the pinnacles. In general, an optimal pinnacle sample size is interplay between achieving dominant features (requires more pinnacles) and reducing the lengthy analysis of new pinnacles (requires less pinnacles). It is worth noting that some pinnacles might offer a solution completely novel to the generalities. While these can be considered, they are not the focus of this research. The number of pinnacles is further addressed in section 3.5.4.

3.5.3 Analyses of selected pinnacles

Each pinnacle obtained from the previous phase is analysed to extract the main principle of performance. This process elaborates on the strategy applied by the pinnacle and abstracts the main principle to be applied in the next phase of the design process.

The steps carried out in pinnacle analysing are as follows. First, the strategy of performance is analysed; second, the relevant mechanism is emphasized; third, the main principle is extracted; and last, the main feature of the performance is indicated (Figure 3.7).

Figure 3.7

Pinnacle analysis. Distinguish strategy, mechanism, main principle, and main feature.

3.5.4 Design path matrix

The challenging transformation from the biological domain to the engineering domain can be investigated under several identified categories, e.g. anatomy, behaviour, ecology [Eroglu *et al.* 2011]. One of the aims of this section is to identify relevant classification categories for pinnacles that have analogies to the functions of building envelopes. The proposed categories are detailed in Table 3.4.

The exploration model (Figure 3.3) may identify numerous pinnacles. Consequently, various strategies, mechanisms, principles, and features are distinguished. The complexity of solutions rises with the number of pinnacles and their various features. In order to reduce this complexity, for each specific function an *imaginary pinnacle* is derived. Each category of the imaginary pinnacle consists of a feature dominant among features of the selected pinnacles at the same category. Thus, the imaginary pinnacle, similar to the selected pinnacles, acquires the same function. This process is analogous to *convergent* *evolution*[2], where independent organisms obtain the same trait (function or structure). Convergent evolutions of organisms, in general, and of selected pinnacles and a derived imaginary pinnacle in particular are illustrated in Figure 3.8.

The dominant features of the various categories (Table 3.5) represent the imaginary pinnacle. As a result, each specific function is represented by one pinnacle –imaginary. This is significant when addressing multiple functions, where numerous pinnacles might be identified, and next step would be superposing only the imaginary pinnacles instead of all pinnacles. For this purpose, a design path matrix has been developed with the

Table 3.4 Pinnacle classification categories.

Functions	**Processes**	**Flow**	**Adaptation**	**Scale**	**Environmental context**	**Morphological features**	**Material features**	**Other**
Air Move air Exchange air **Heat** Gain heat Retain heat Dissipate heat Prevent heat **Water** Gain water Conserve water Transport water Lose water **Light** Regulate light intensity Minimize light reflections	Diffusion natural convection condensation capillary action . . .	Active passive	Physiological Morphological Behavioural	Nano micro meso macro	**A Equatorial*** Af Equatorial rainforest, fully humid Am Equatorial monsoon As Equatorial savannah with dry summer Aw Equatorial savannah with dry winter **B Arid climates*** BS Steppe climate BW Desert climate **C Warm temperate climates*** Cs Warm temperate climate with dry summer Cw Warm temperate climate with dry winter Cf Warm temperate climate, fully humid **D Snow climates*** Ds Snow climate with dry summer Dw Snow climate with dry winter Df Snow climate, fully humid **E Polar climates*** ET Tundra climate EF Frost climate **Q Aquatic**	Hexagons Fibonacci fractals conduits funnels mounds . . .	Elasticity viscosity porosity . . .	Bernoulli counter-current flow unidirectional flow surface volume ratio .

* According to Köppen classification, adapted from [Kottek *et al.* 2006].

2 Convergent evolution is the acquisition of the same trait (function or structure) by organisms of independent ancestors.

objective to indicate the successful aspects to be implemented in the design concept. The design path matrix is based on the categories presented in Table 3.4. The design path matrix classifies and categorizes each imaginary pinnacle with its specific path (dotted lines of red, blue, and green in Table 3.5), and distinguishes the dominant feature of each category (highlighted node in orange in Figure 3.9). The dominant feature is the feature that has the highest overlap among the imaginary pinnacles. Dominant features of the various categories determine the relevant aspects: implemented process (e.g. diffusion), flow strategy (passive or active), type of adaptation (e.g. morphological), scale for performance (e.g. nano), environmental context (e.g. Aw), morphological features (e.g. hexagons), structural features (e.g. chimney), material features (e.g. elastic), and any other relevant feature (e.g. capillary action).

Achieving a dominant feature in a category depends on the number of imaginary pinnacles relative to the number of features in the category. For categories containing at least three features the probability to obtain a dominant feature increases with the sample size of imaginary pinnacles – the larger the sample size the more probable obtaining dominance becomes. The number of imaginary pinnacles and the obtained dominant features are strongly dependent on the specific challenge and selected pinnacles as further elaborated in the following chapters.

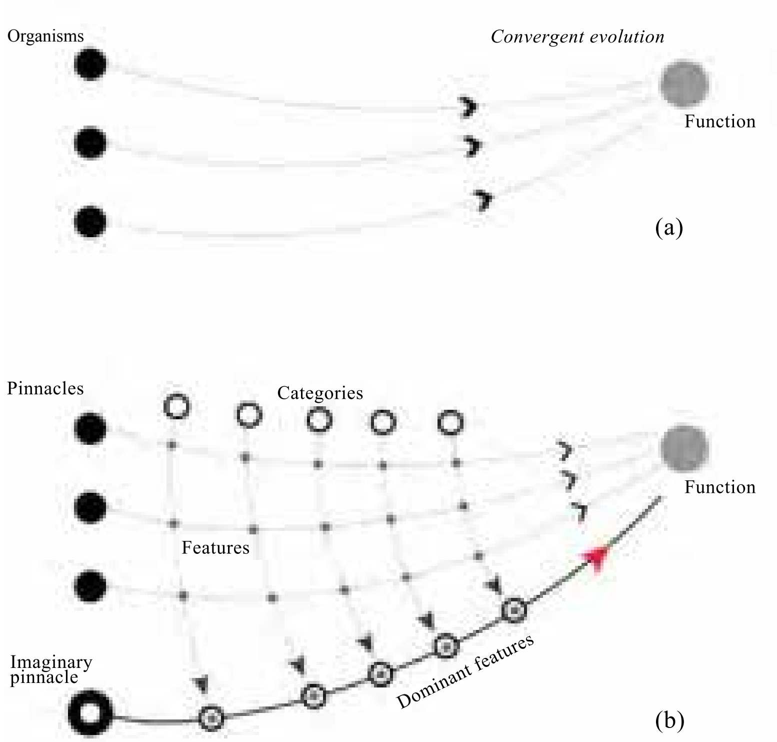


Figure 3.8

Convergent evolution of: (a) organisms in general; (b) selected pinnacles and derived imaginary pinnacle.

Pinnacle analysing matrix. An example for generating Imaginary pinnacles (highlight in red, green, and blue) for specific functions (F1- F3), which has the dominant feature from each category (vertical column).

Table 3.5

		Processes			Flow		Adaptation			Scale				Environmental context (from Table 3.4)						Morphological features							Material features			Other features				
Challenge	**Pinnacles**	Diffusion	Natural Convection	Etc ...	Active	Passive	Physiological	Morphological	Behavioural	Nano	Micro	Meso	Macro	A	B	C	D	E	Q	Funnels	Mounds	Fractals	Valves	Chimney	Conduits	Etc ...	Porous	Elastic	Etc ...	Counter-current flow	Contracting	Enlarged surface area	Unidirectional flow	Etc...
	P1	X				X		X			X			X	X	X	X					X			X			X			X			
	P2	X				X		X			X				X							X					X			X		X		
	P3		X		X			X			X			X	X	X	X						X					X				X		
Function 1	(*imaginary* pinnacle)	X				X		X			X				X							X						X				X		
	P4			X		X		X				X				X	X							X								X		
	P5	X				X		X				X					X						X		X			X				X		
	P6	X				X			X		X					X	X								X			X			X			
Function 2	(*imaginary* pinnacle)	X				X		X				X					X								X			X				X		
	P4			X	X			X				X					X				X						X					X		
	P5	X			X			X				X					X			X		X					X					X		
	P6	X			X		X						X			X						X						X			X			
Function 3	(*imaginary* pinnacle)	X			X			X				X					X					X					X					X		

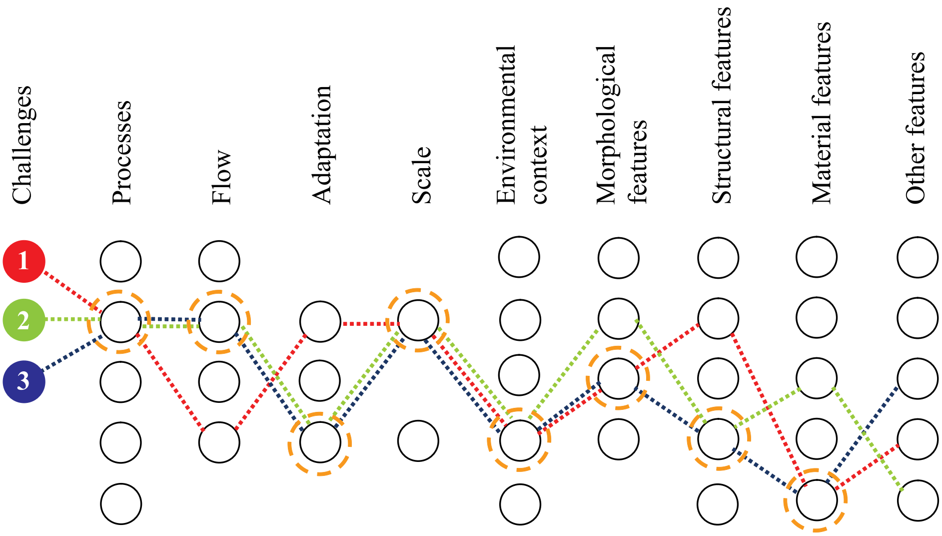


Figure 3.9

Design path matrix. Each vertical column represents a category and its various features. Red, green, and blue lines denote the path of the imaginary pinnacles. The orange nodes denote the dominant feature of each category, which represent the design concept path.

3.5.5 Preliminary design concept proposal

The superposition of the dominant features extracted from each category set the design concept layout (the dashed circles in Figure 3.9). For example, the challenge is that an aimed living envelope has to collect water from fog, and transport it over the surface. Provided that as a result of the design path matrix the following dominant features are obtained: (1) hydrophilic bumps for water collection; (2) hexagons for the arrangement of the repeating elements; and (3) micro channels for transporting water through capillary action. In this case the three dominant features are superposed leading to a design concept layout.

3.6 Conclusions

A systematic methodology for the design concept generation of adaptive building envelopes was presented. The design method investigates natural organisms and systems that provide a self-regulating living environment with the ability to respond to changing internal and external conditions. The design method seeks a convergence between adaptation challenges of a building envelope and solutions found in nature, through biomimetics. Such a convergence leads to the emergence of the living envelope. The living envelope is a term used in the current work to describe an envelope that has the ability to adapt to the changes arising in the surrounding environment in order to maintain a comfort state for its occupants.

In order to develop a living envelope, there is a need to proceed with a number of phases and sub-phases, such as identifying the demands, exploring and extracting principles from nature, obtaining concept designs, evaluating the designs, transforming chosen ideas into concept design solutions. A flow chart that guides the architect through the design process was presented (Figure 3.2).

The design process consists of a preliminary design phase and an emulation phase, Note that the focus of this thesis is on the preliminary phase. The preliminary design phase is divided into three main sub-phases: (1) the exploration model, (2) the pinnacle analysing steps, and (3) the design path matrix. These sub-phases were presented in unique schemes (Figures 3.3, 3.6, 3.7, & 3.9, Tables 3.4 & 3.4).

The summary of nature's investigation presented in the exploration model is based on four levels: functions, processes, factors, and pinnacles. These levels guide the architect through the decision taking process, leading to representative pinnacles based on the initial design challenge. The representative pinnacles are analysed and applied in the pinnacle analysing matrix (Table 3.5), where imaginary pinnacles are sought for each particular challenging function. These imaginary pinnacles are applied in the design path matrix (Figure 3.9), which results in a unique dominant path. This dominant path is distinguished as a result of overlaying various imaginary pinnacles. Thus, the design path matrix results in a path that combines between all the dominant features – the features of which can be emulated to create an integrated design concept for living envelopes.

In summary (Figure 3.10), the *living envelope* methodology creates an exploration and investigation platform for the architect and helps channel a way from technical challenges, through functional aspects in nature, to various possible strategies found in nature. Furthermore, the methodology provides several phases of categorizations that funnel at the end into a design concept outline based on imaginary pinnacles that have the successful dominant features.

The next chapters (4, 5, 6 & 7) demonstrate the implementation of the living envelope methodology to solve particular problems, identify relevant biological phenomena, and illustrate the various potentials of concept design solutions.

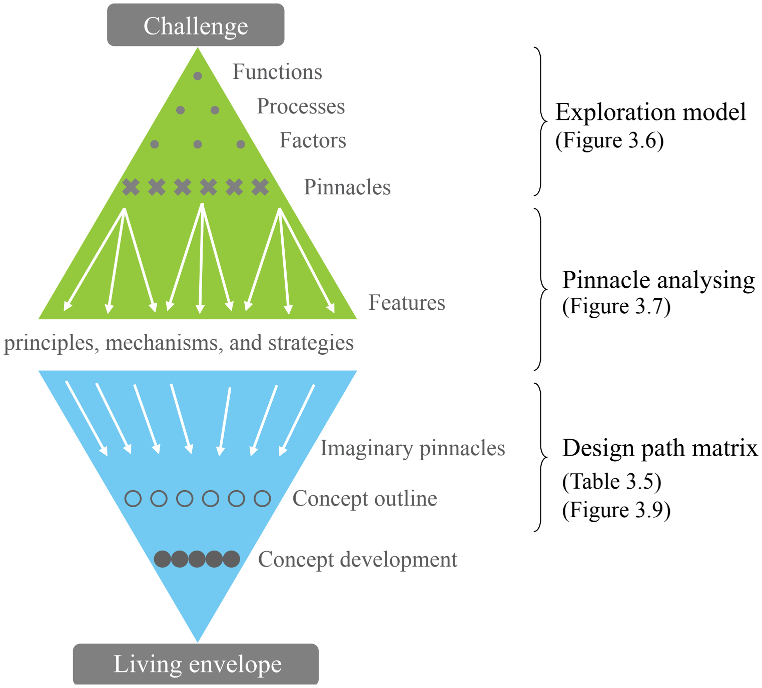


Figure 3.10
The concept of the living envelope methodology.

References

AskNature – a project of Biomimicry 3.8, available online at: www.asknature.org (retrieved December 2011)

Badarnah, L., [2009]. *Nature Inspired Envelope Innovation: A design workshop in Biomimicry*. May 2009, Delft University of Technology, the Netherlands.

Badarnah, L., Nachman Farchi, Y., and Knaack, U., [2010]. Solutions from nature for building envelope thermoregulation, *Proc. of the fifth Design & Nature Conf.: Comparing Design and Nature with Science and Engineering*, Carpi A & Brebbia CA eds., pp. 251-262 (Southampton: WITpress).

Badarnah, L., Rietbergen, D., and Knaack, U., [2008]. *The Future Envelope Workshop*. May 2008, Delft University of Technology, the Netherlands.

Baumeister, D., [2012]. *Biomimicry Resource Handbook: a seed bank of knowledge and best practices*. The Biomimicry Group.

Benyus, J.M., [2002]. *Biomimicry: Innovation inspired by nature*, New York: HarperCollins publishers.

Biomimicry 3.8, available online at: http://biomimicry.net/ (retrieved December 2011)

Bogatyreva, O., Pahl, A.-K., and Vincent, J.F.V., [2002]. Enriching TRIZ with biology. TRIZ Future, 2002: *Proceedings ETRIA World Conference*, Strasbourg, pp. 301-308.

Bogatyreva, O., Pahl, A.-K., Bowyer, A., and Vincent, J.F.V., [2003]. Data gathering for putting biology in TRIZ. *Proceedings of TRIZcon 2003*, Altshuller Institute, USA, 16–18 March.

Chiu, I. & Shu, L.H., [2007]. Biomimetic design through natural language analysis to facilitate cross-domain information retrieval. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **21**, pp. 45-59.

Craig, S., Harrison, D., Cripps, A., and Knott, D., [2008]. BioTRIZ suggets radiative cooling of buildings can be done passively by changing the structure of roof insulation to let longwave infrared pass. *Journal of Bionic Engineering*, **5**, pp. 55-66.

DANE – *Design by Analogy to Nature Engine*, available online at: http://dilab.cc.gatech.edu/dane/#LearningSBFTab (retrieved December 2011).

Eroglu, A.K., Erden, Z., and Erden, A., [2011]. Biological system analysis in biological conceptual design (BICD) for bioinspired robots. *Control Engineering and Applied Informatics*, **13**(2), pp. 81-86.

Gebeshuber, I.C. & Drack, M., [2008]. An attempt to reveal synergies between biology and mechanical engineering, Proceedings of the IMECHE, Part C: *Journal of Mechanical Engineering Science*, **222**(7), pp. 1281-1287.

Goel, A.K., *Design & Intelligence Laboratory*, Georgia Institute of Technology, available online at: http://home.cc.gatech.edu/dil/3 (retrieved December 2011).

Goel, A.K., Rugaber, S., and Vattam, S., [2009]. Structure, Behavior & Function of Complex Systems: The Structure-Behavior-Function Modeling Language. International *Journal of AI in Engineering Design, Analysis and Manufacturing*, Special Issue on Developing and Using Engineering Ontologies, **23**, pp. 23-35.

Gruber, P., Bruckner, D., Hellmich, C., Schmiedmayer, H.-B., Stachelberger, H., and Gebeshuber, I.C. (eds.), [2011]. *Biomimetics – Materials, Structures, and Processes: Examples, Ideas and Case Studies*, London: Springer.

Gruber, P., [2011]. *Biomimetics in Architecture: architecture of life and buildings*, Vienna: Springer.

Helms, M., Vattam, S.S., and Goel, A.K., [2009]. Biologically inspired design: process and products. *Design Studies*, **30**(5), pp. 606-622.

Hill, R.W., Wyse, G.A., and Anderson, M., [2008]. *Animal Physiology*, Massachusetts: Sinauer Associates Inc.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. [2006] World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.*, **15**, pp. 259-263. DOI: 10.1127/0941-2948/2006/0130.

Lerner, L., [1991]. Genrich Altshuller: Father of TRIZ. Ogonek (Russian Magazine), available online at: http://www.aitriz.org/articles/altshuller.pdf

Mak, T.W. & Shu, L.H., [2004]. Abstraction of Biological Analogies for Design. *CIRP Annals*, **53**(1), pp. 117-120.

Masselter, T. Haushahn, T., Schwager, H., Milwich, M., Nathanson, R., Gude, M., Cinchy, F., Hufrnbach, W., Neinhuis, C., and Speck, T., [2010]. Biomimetic fibre-reinforced compistes inspired by branched plant stems. *In Proc. of the fifth Design & Nature Conf.: Comparing Design and Nature with Science and Engineering*, Carpi A & Brebbia CA eds., pp. 411-420, Southampton: WITpress.

Milwich, M., Speck, T., Speck, O., Stegmaier, T., and Planck, H., [2006]. Biomimetics and technical textiles: solving engineering problems with the help of nature's wisdom. *American Journal of Botany*, **93**(10), pp. 1455-1465.

PBG – Plants Biomechanics Group. The Botanic Garden of the University of Freiburg, available online at: http://www.botanischer-garten.uni freiburg.de/profile_Freiburg_ English.htm (retrieved December 2011).

Schmidt-Nielsen, K. [2007]. *Animal physiology: adaptation and environment*, New York: Cambridge University Press.

Shu, L.H., [2010]. A natural-language approach to biomimetic design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **24**, pp. 507-519.

Shu, L.H., *Department of Mechanical and Industrial Engineering*, University of Toronto, available online at: http://www.mie.utoronto.ca/labs/lcdlab/shu/ [retrieved December 2011].

Speck, T., Harder, D.L., Milwich, M., Speck, O., and Stegmaier, T., [2006]. Bionik: Die Natur als Innovationsquelle für Technische Textilien. Knecht P. ed., *Technische Textilien*, pp. 83–101, Frankfurt: Deutscher Fachverlag.

TRIZ, *The Altshuller Institute for TRIZ Studies*, available online at: http://www.aitriz.org/ (retrieved December 2011).

Vakili, V. & Shu, L.H., [2001]. Towards biomimetic concept generation. P*roceedings of 2001 ASME Design Technical Conferences, Design Theory and Methodology Conference*, Pittsburgh, PA, USA, DETC2001/DTM-21715.

Vattam, S., Helms, M., and Goel, A.K., [2007]. Biologically Inspired Innovation in Engineering Design: A Cognitive Study. *Technical Report*, Graphics, Visualization and Usability Center, Georgia Institute of Technology, GIT-GVU-07-07.

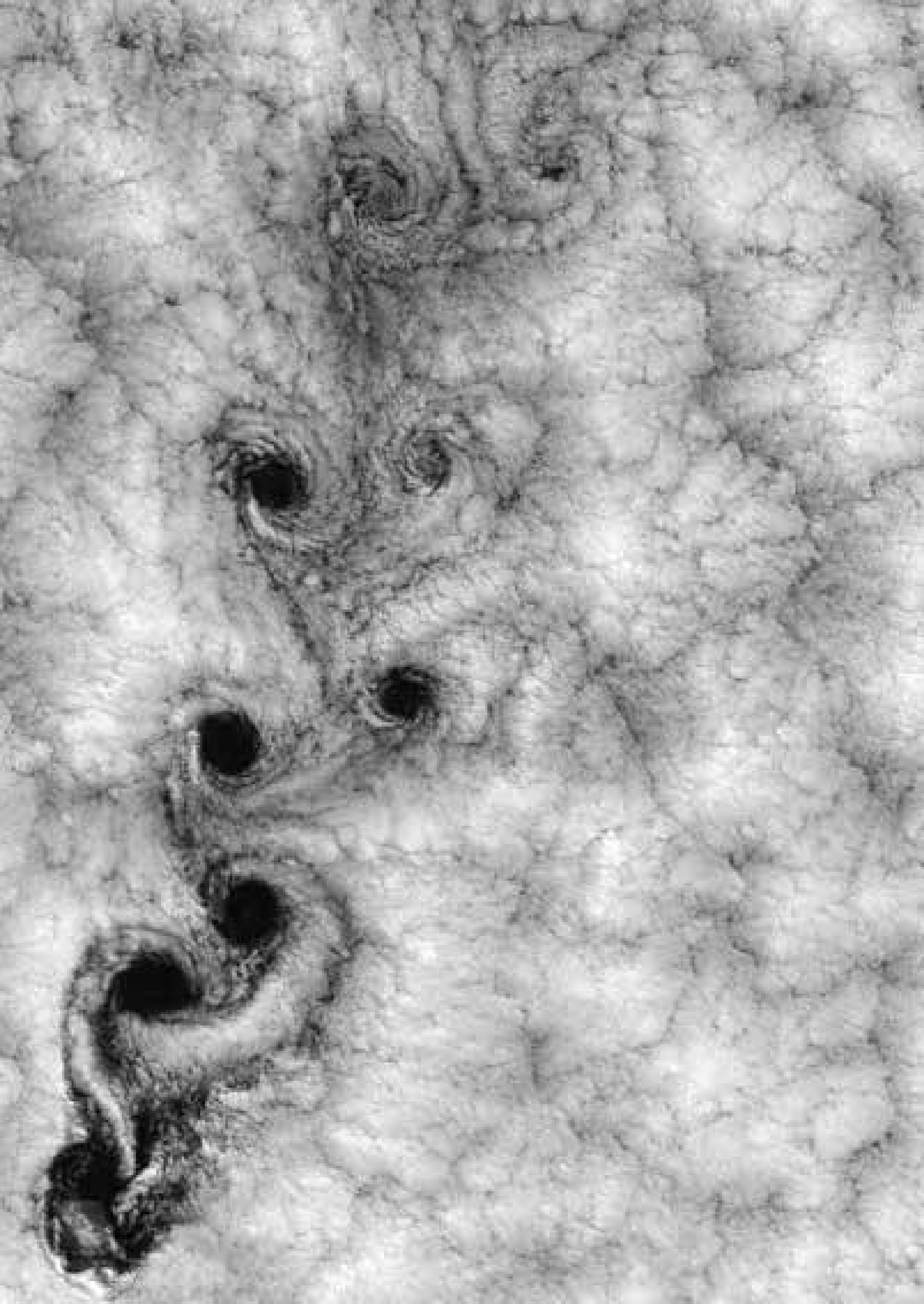
Vattam, S., Helms, M., and Goel, A.K., [2009]. Nature of creative analogies in biologically inspired innovative design. *Proceedings of 7th ACM Conference, Creativity and Cognition*, Berkely, CA, USA, pp. 255-264.

Vattam, S., Wiltgen, B., Helms, M., Goel, A.K., and Yen, J., [2010]. DANE: fostering creativity in and through biologically inspired design. *Proceedings of 1st international conference on Design and Creativity*, Kobe, Japan, pp. 115-122.

Vincent, J.F.V., Bogatyrev, O.A., Bogatyreva, N.R., Bowyer, A., and Pahl, A.K., [2006]. Biomimetics – its practice and theory. *Journal of the Royal Society Interface*, **3**, pp. 471-482.

Vincent, J.F.V., [2009]. Biomimetics - a review. Proceedings of the Institution of Mechanical Engineers, Part H: *Journal of Engineering in Medicine*, **223**(8), pp. 919–939.

Vogel, S., [1989]. *Life in moving fluids: the physical biology of flow*, Princeton: Princeton University Press.



Air

Chapter **4**

4.1 Introduction

The primarily focus in current ventilation system developments is to reduce indoor air quality problems with minimal energy use [Addington 2000]. Inadequate indoor air quality might lead to *sick building*[1] syndrome. Several guidelines and requirements in terms of air quality have been investigated and introduced to avoid any negative effects. For example, ASHRAE standards have extensive information on the acceptable indoor air quality for various types of buildings [ASHRAE 2004]. In order to address indoor air quality, ventilation is provided.

Ventilation in buildings is provided either naturally or mechanically. In natural ventilation, the flow process is induced by wind and temperature [Liddament 1996], and the main negative aspect is the difficulty to control airflow. Nonetheless, natural ventilation is found in many buildings and found to be preferred by the occupants, especially windows. Windows can provide cross ventilation, which are operated by occupants thus increase acceptance of the indoor environmental conditions [Nicol *et al.* 2008]. However, occupants tend to leave windows open for long periods, which creates situations of continuous outdoor air supply to the occupied spaces and often results in high airflow rates [Perino 2009]. Besides the common cross ventilation principle, other basic principles are applied in buildings such as natural convection and pressure differentials (see Figure 4.1).

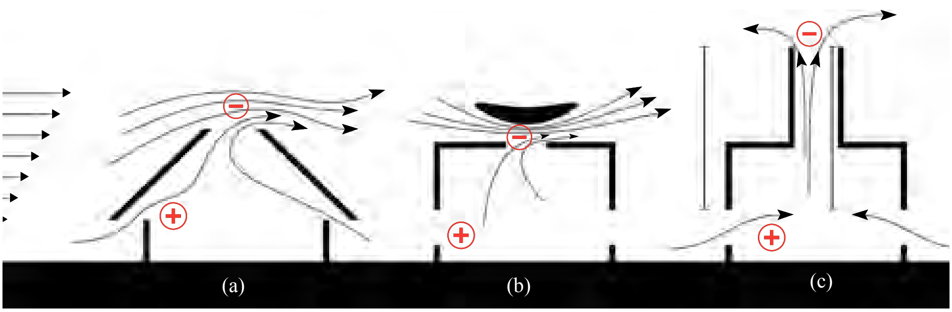


Figure 4.1

Natural ventilation by natural convection or pressure differential. (a) *Bernoulli & Coanda effect*: air velocity increases with height and follows the concave shape of roof, thus creates a pressure drop at the roof, as a result, air is expelled out of the roof and fresh air is driven inside. (b) *Venturi effect*: velocity increases at the constriction region and a negative pressure is generated, which expels the air out and as a consequence drives air in. (c) *Stack effect* (natural convection): hot air is exhausted due to temperature gradient, e.g. when temperature inside is larger than the temperature outside.

1 Sick building syndrome is the association of discomfort experienced by building occupants due to poor conditions of air quality and other aspects related to indoor climate.

The consideration of energy conservation in modern buildings resulted in airtight building envelopes, which prevent air infiltration through the building envelope. As a result, mechanical ventilation systems have become necessary both to supply and exhaust air. Mechanical ventilation systems control airflow via components distributed in the building using methods such as extract-only, supply-only, supply and exhaust or balanced, and recirculation [Roulet 2008]. Some of them have the risk of back draught from flues, and others require empty floor spaces in order to allow airflow from diffusers places in the floor [Liddament 1996]. Mechanical ventilating systems include several components: fans, ducts, diffusers, air-intakes, air-inlets, air grilles, and silencers [Liddament 1996], where these isolated components are assembled together to create the overall ventilating system and have to be maintained from time to time [Roulet 2008]. In this respect, *hybrid ventilation*[2] solutions might overcome the negative effects of both methods, while utilizing their efficiency.

Air exchange and movement are significant functions in nature, as organisms need oxygen to survive. The efficient active and passive solutions in nature might promote the design of innovative hybrid ventilation systems for building envelopes, and result in better indoor air quality with less energy consumption.

The current chapter explores and investigates air regulation strategies in nature for implementation in ventilation systems for building envelopes, based on the *living envelope methodology* presented in chapter 3. Many living organisms in nature perform air exchange in order to supply their active tissues with oxygen, by direct or indirect means. Various systems and structures of respiratory organs have evolved to perform and facilitate air exchange processes. A brief background on some selected air exchange and movement strategies in nature, with a focus on air diffusion, convection, and pressure differential, are given in section 4.2. The investigated functions, processes, factors and pinnacles are summarized in the *exploration model* in section 4.3. An example of a design concept generation for a hybrid ventilation system based on principles derived from the *exploration model* and *design path matrix* is presented in sections 4.4. The active ventilating component acts as a breathing medium that has the ability to control the amount of intake and outlet of air through [Badarnah & Knaack 2007]. The system is a combination of natural and mechanical ventilation, where the components create pressure differences that suck air through the envelope. The passive ventilating component is based on the principles of physical laws found in termite mounds and tracheal systems in insects. The architectural features of the biological systems were adapted to the system to facilitate gas exchange passively. Finally, the concluding remarks are given in section 4.5.

4.2 Air regulation in nature

One of the objectives of gas regulation, carried out by most organisms, is oxygen uptake and carbon dioxide release (or vice versa), which is required for energy matters in the process of food and materials oxidation [Schmidt-Nielsen 2007]. This process of gas exchange is performed via diffusion, and further elaborated in section 4.2.1. Organisms

2 Hybrid ventilation is the combination of mechanical and natural ventilation.

have developed various strategies to maintain the required gas concentration levels whether in their bodies or in their immediate surrounding environment (such as that found in their homes or structures).

Animals construct their structures, among other reasons, for protection against extremes of climates. Gas exchange may rise as a secondary problem from creating protective walls, which then adds to the complexity of the structure's functional design [Hansell 2007]. As such, the structure (nature's architecture) may provide ways to maintain environmental optima (*homeostasis*). Velocity gradients generated across surfaces provide potential source of work, which might be employed by, e.g., a burrowing animal to induce gas exchange in its long and narrow burrow [Vogel *et al.* 1973]. Numerous studies have been carried out about the animals as architects and their constructions [e.g. Lavine 1964, Gould & Gould 2007, Hansell 2005, 2007].

To further understand the role of gas exchange in organisms, the mechanisms of gas movement in nature and their effect on the physiology of organisms might be explained by the basic laws of physics in general [Vogel 1989], and of fluid dynamics in particular. For this reason, some basics of fluid dynamics are introduced with a special focus on natural convection (section 4.2.2), and pressure differences (section 4.2.3).

4.2.1 Air exchange via diffusion

Diffusion[3] is an important physical process for gas exchange. Many small organisms obtain the sufficient amount of oxygen by diffusion via their body surface (e.g. many amphibians like frogs and salamanders), whereas most organisms require a special respiratory system for oxygen uptake. Oxygen uptake via skin is almost constant throughout the year; this is due to the concentration of oxygen in the atmosphere, which provides a constant diffusion [Schmidt-Nielsen 2007]. Surface-volume ratio, concentration gradient, and permeability, affect diffusion rate [Gillott 2005]. Various systems and structures of respiratory organs have evolved to increase the rate of diffusion and facilitate the exchange of gases.

4.2.1.1 Surface-volume ratio

An enlarged surface area for diffusion can be achieved through morphological adaptation of the respiratory organ. Respiratory systems are organs integrated in the body responsible for gas transport and exchange. The respiratory organs of aquatic breathing are different from those for air breathing, due to oxygen concentration level differences ($<1\%$ oxygen in water, compared to $\sim 21\%$ in air). The stratified anatomical structure of gills (the respiratory organ of fish) allows a high water flow over the tissues and a counter-current flow of water over the blood-rich tissues, which enhances gas exchange. The gills consist of numerous gill arches on each side, where each arch is carrying two rows of gill filaments (see Figure 4.2). These filaments carry thin parallel, plate-like lamellae, where the blood flows in the opposite direction of water flowing between these lamellae [Randall 1968].

3 Diffusion is the substance flow from higher to lower concentration.

This arrangement allows an enlarged surface area for gas exchange in the gill. Morphological adaptation of the respiratory organ greatly influences gas exchange efficiency, where *fractal*[4] structures are distinguished among these organs to enhance gas exchange rates [Losa *et al.* 2005]. Fractals are complex structures that have a large surface area within a confined space. One of the dominant fractal models is the Koch tree (Figure 4.3), where a constant factor reduces branch diameter and length. Fractals can be found in different body sizes, e.g. from 2 gr (in a shrew) up to 500 kg (in horses) [Weibel 2005]. In gills, the fractal construction is at a lower dimension than the mammalian lungs. This could be explained by the fact that the gills have an efficient counter current flow of water and blood [Maina 2002].

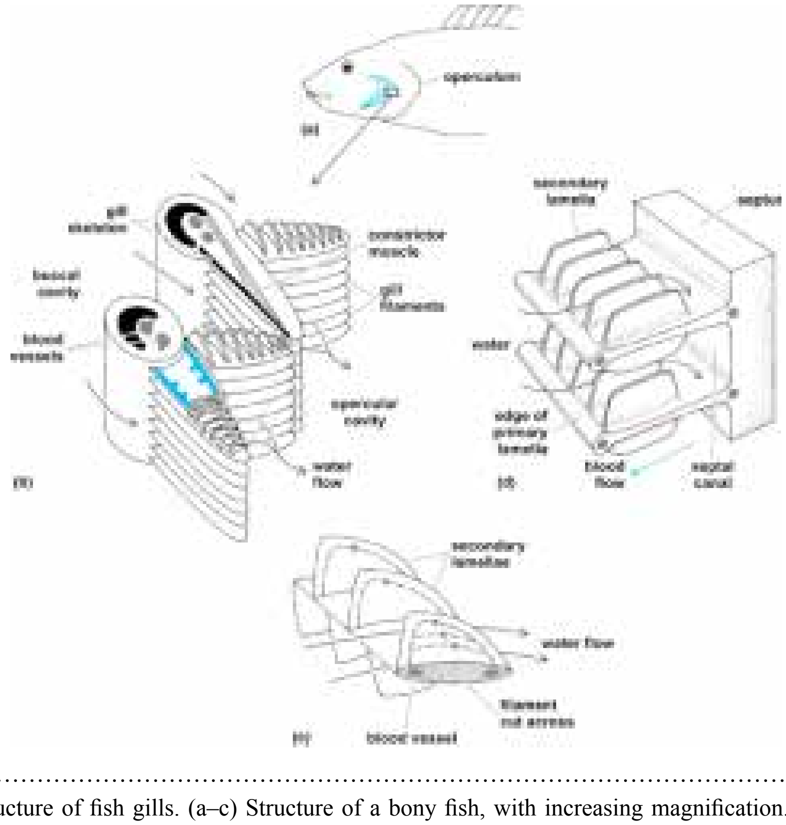


Figure 4.2

Structure of fish gills. (a–c) Structure of a bony fish, with increasing magnification. (d) Elasmobranch gill at the same magnification as c. Black arrows show path and direction of water flow. Reproduced from McEwen *et al.* [2008], used with permission from McGraw-Hill companies.

4 Fractal is a geometrical description of systematic branching structures, where a constant factor reduces the size (length and diameter) of a branch from one generation to the next, e.g. the Koch tree model [Mandelbrot 1977].

The minimized energy dissipation due to fractals is proposed theoretically in the *Hess-Murray law*, which proposes an energy efficient flow in a branched system to when the diameter of the two daughter-branches d_1 and d_2 are related to the diameter of the parent branch d_0 as $d_0^3 = d_1^3 + d_2^3$ [Hess 1914, Murray 1926].

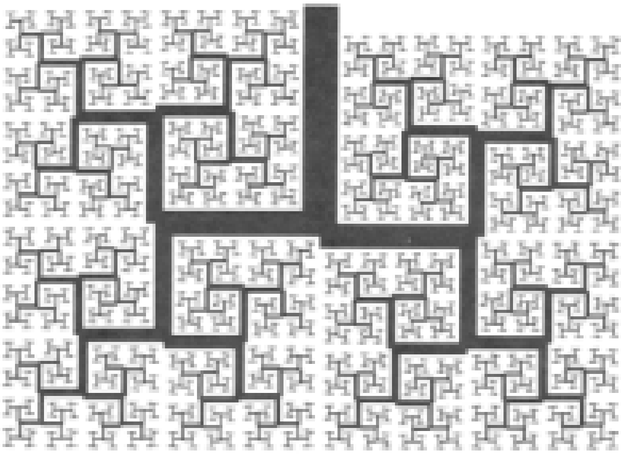


Figure 4.3

Koch tree model of airways: "*a self-similar space-filling fractal based on dichotomous branching whereby the size of the daughter-branches is reduced by the same factor from one generation to the next*" [Mandelbrot 1977]. Reproduced from Mandelbrot [1977], used with permission from W.H. Freeman & Company/Worth Publishers.

4.2.1.2 Permeability

The permeable shell structure of an egg functions as a filtering medium between the organism and the surrounding environment. The hard shell of an egg besides providing protection to the growing embryo is permeable to gases. For example, the eggshell of a hen has about 10,000 pores with a diameter of 0.017 mm each, and a total pore area of 2.3 mm^2. The surface area of the egg is about 70 cm^2, and has an average of 1.5 pores per square millimetre of shell. These pores are responsible for gas exchange between the embryo and the surrounding environment. Gas exchange is accomplished by diffusion until lung respiration begins [Schmidt-Nielsen 2007]. Variations in shell thickness and pore diameter are found among species from different environments (e.g. different elevations and humidity conditions) for sufficient gas diffusion rates and decreased water loss [Carey 1980, Seymour *et al.* 1986].

Plants have no specialized organ for gas exchange. Their roots, stems, and leaves rely on direct gas exchange through *stomata*[5] . Gas exchange in plants is accomplished by simple diffusion. For example, both photosynthesis and transpiration occur simultaneously in the leaf: carbon dioxide is absorbed during photosynthesis, whereas water and oxygen are expelled.

5 Stomata. Minute pores in the epidermis of a leaf or stem through which gases and water vapour pass.

4.2.1.3 Concentration gradient

High pressure in circulatory systems forces fluids to pass through capillary walls, and osmotic pressure causes fluids to move (an exchange process) between cells and blood [Hill *et al.* 2008]. Gas exchange in lungs occurs at the alveoli, which have an enlarged surface area, thin walls, and are rich with blood capillaries. During gas exchange, gases move from higher concentration to lower concentration: oxygen diffuses from the air in the alveoli into the blood, and carbon dioxide diffuses from the blood into the air in the alveoli (Figure 4.4).

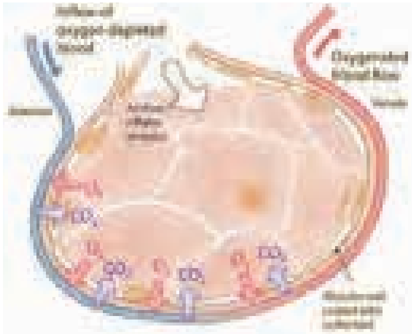


Figure 4.4

The gases move by diffusion from high to low concentration. Courtesy of Nave [2012].

4.2.2 Air movement via natural convection

The driving force for natural convection is *buoyancy*[6], which is a result of variations in fluid density. In natural convection, the increase in temperature of a fluid makes it less dense and results in rising. The surrounding, cooler fluid moves to the lower pressure area to replace the rising fluid. Cooler fluid is heated and the process continues, forming convection current (Figure 4.5). Natural convection phenomena are observed, among others, in oceanic currents and wind formation in nature. Moreover it can be observed in some organisms' dwellings, e.g. termite mounds and wasp nests.

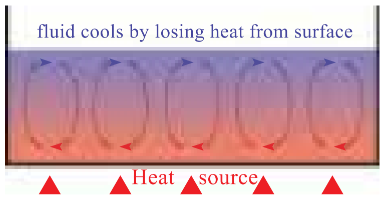


Figure 4.5

Convection currents. Warm, low density fluid rises. Cool, high density fluid sinks.

4.2.3 Air movement via pressure differences

Pressure differences is generated by velocity gradients or volume variations. Fluids move from regions of higher pressures to regions of lower pressures. Consequently, the lowest pressures occur at the highest velocities, and the highest pressures occur at the lowest velocities.

6 The principle of buoyancy states that a body fully or partially submerged in a fluid experiences a lifting force equal to the weight of the displaced fluid.

4.2.3.1 Velocity gradient

According to the principle of continuity, stated simply, if a defined volume of an incompressible fluid enters one end of a medium then the same volume has to come out the other end. The principle of continuity relates the velocity of the moving fluid through a pipe to the cross-sectional area of the pipe, e.g. *Venturi effect*: a decrease in the cross-sectional area results in an increase of the fluid average velocity, and vice-versa (as presented in Figure 4.6). According to Bernoulli's principle, the increase in velocity is accompanied with a decrease in pressure. Figure 4.7 presents three different configurations of flow systems, at which flow is induced in the small curved pipe due to velocity gradient at the two ends of the small pipe. In Figure 4.7a, the negative velocity gradient between points 1 and 2 is accompanied with a positive pressure gradient in the curved pipe resulting in an induced flow from point 2 to point 1. In the case of a small pipe perpendicular to a larger channel, as shown in Figure 4.7b, the size of the opening influences the rate of viscous entertainment, which results in sucking (towards the larger opening). In this case the induced flow travels from point 1 to point 2. In the case of a bent small pipe at 90° angle, positioned in a stream, as shown in Figure 4.7c, the water enters at the opening normal to stream flow and exit from the upstream opening, since the pressure at the upper opening (point 2) is lower as the velocity is highest in the middle. In this case, the flow direction is from point 1 to 2.

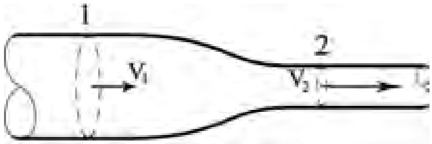


Figure 4.6

Venturi effect: a decrease in the cross-sectional area (from 1 to 2) results in an increase of the fluid average velocity (from v_1 to v_2).

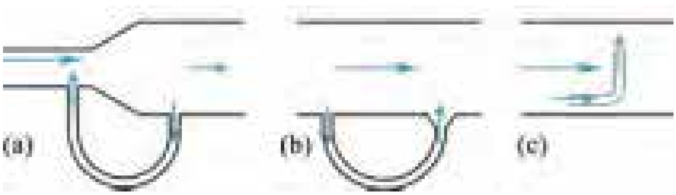


Figure 4.7

Flow induced into a small pipe from a larger channel due to pressure differences. The arrows indicate the vectors of the different velocities (after Vogel 1974).

4.2.3.2 Volume variations

Volume variations are active flow means for fluid (gas or liquid) transportation in the circulatory system of an organism, where diffusion is inadequate or too slow. These circulatory systems depend on pumps and tubes through which the fluid flows, e.g.

hearts and lung's diaphragm; both have a significant role in transporting liquid[7] and gas, respectively. The heart is a blood pump found in vertebrate and invertebrate animals with the ability to contract and expand in order to reduce and increase its volume. A basic purpose of the heart is to force the blood to flow and reach all body parts and return back in some cases. Elastic tubes (e.g. veins, arteries, capillaries) carry the blood in vertebrate, and the blood remains in a closed system with a specific range of pressure. There are three types of pumps (Figure 4.8) that move the blood around in the body [Schmidt-Nielsen 2007].

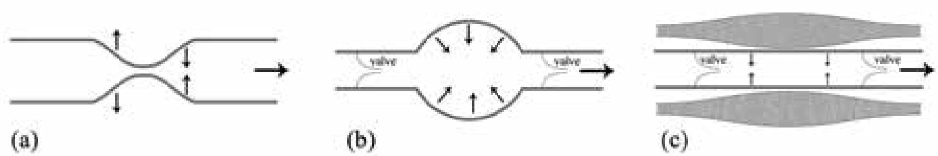


Figure 4.8

Three types of pumps moving blood in a circulatory system [Schmidt-Nielsen 2007]: (a) *The peristaltic pump*: mostly found in invertebrates; a constriction in a tube moves along the tube and pushes blood ahead. (b) *The common chamber pump*: the walls contract and reduce volume; it is characterized by rhythmical contractions of the walls and force blood out, where the valves control the flow in one direction and prevent backflow. (c) *Chamber pump*: reduces volume by external pressure of other body parts; it is found in the larger veins in human legs, to ensure blood backflow to the heart and prevent blood accumulation in legs because of gravity; the veins are provided with valves that control the flow in one direction and prevent backflow (after Schmidt-Nielsen 2007).

4.3 Exploration model for air regulation

The previous sections of this chapter defined the various entities of the exploration model, and discussed their interrelationships. The investigation and exploration of air regulation in nature is based on two initial functions: exchange and movement (see Figure 4.9). Each function incorporates different processes, where some are indicated in the exploration model for air regulation (Figure 4.9). The exploration model is classified based on four levels. On the first level the functional aspects are identified: air exchange and air movement. The second level of exploration distinguishes the processes that manipulate the identified functional aspects, e.g. natural convection. The influential factors affecting the distinguished processes are explored on the third level, e.g. temperature gradient. These factors lead to the fourth level of exploration, where pinnacles represent a particular function, e.g. termite mound for air movement. The content of the presented model is a representative state for the current exploration, where it can be extended and new entities at the various levels may be added in future elaborations. The systematic representation of entities and their relationships support the access to relevant information, which is further discussed in the following section by an example.

7 For air regulation one may examine both gas and liquid flow systems, as both obey the same fluid dynamics rules.

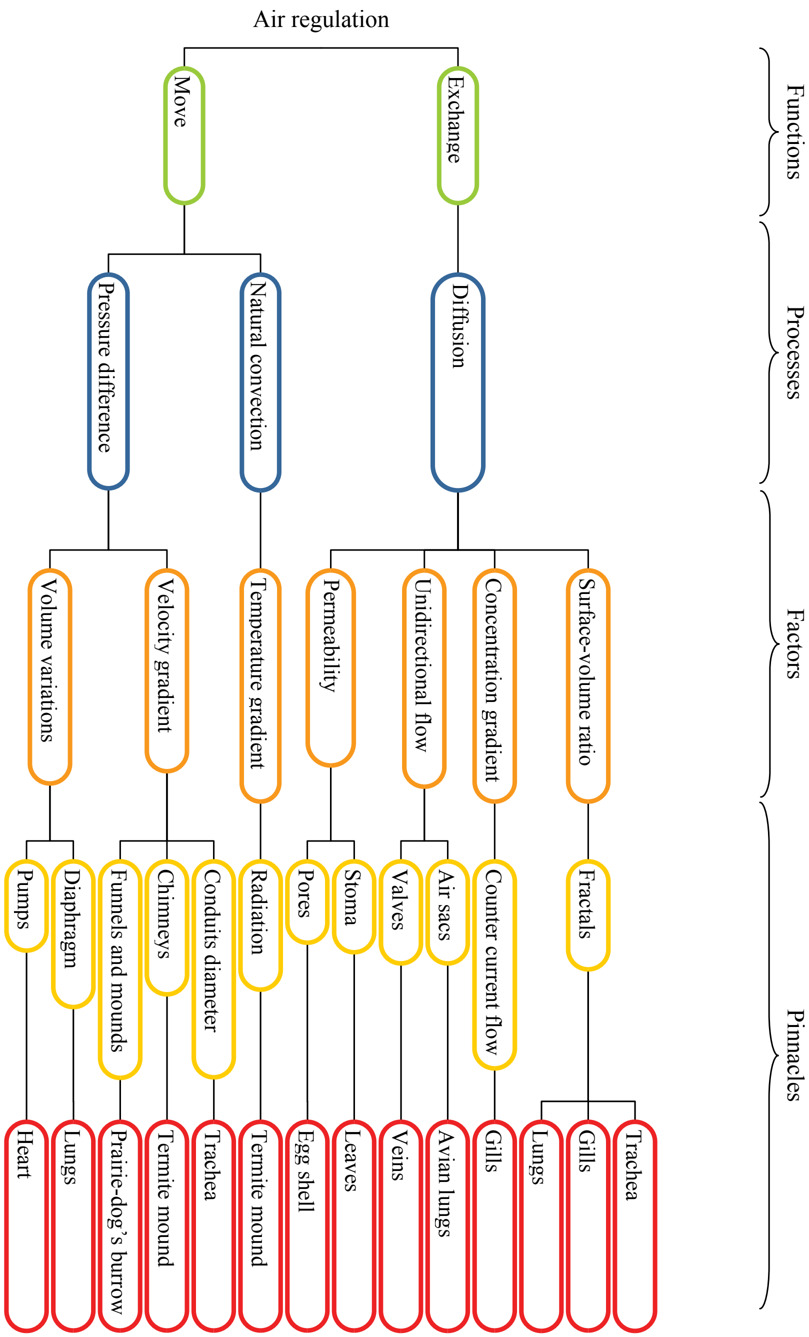


Figure 4.9 ……………………………………………………………………………………….

Exploration model for air regulation

……………………………………………………………………………………………

4.4 Example: ventilation system

One of the basic requirements for human health and wellbeing in buildings is adequate indoor air quality. Air is supplied to indoor environments by natural or mechanical means. Emerging technologies for building envelopes, that seek air and water tightness, result in less interaction with the surrounding environment, where potentials for natural air exchange are not utilized. As a consequence, the demand for mechanical ventilation systems increases, which increases energy demands.

The consideration of passive ventilation principles together with mechanical ventilating components for control might be a promising approach for efficiency and increased occupant satisfaction [Raja *et al.* 2001]. This could be achieved by the passive exchange of air without passing through complex mechanical systems, and the enhancement of air movement via mechanical means when passive air exchange is inadequate. The following sections demonstrate an example for generating a design concept. The steps of the concept generation are based on the methodology presented in chapter 3.

4.4.1 Definition of the design challenges (step 1)

The challenge defined for the current design is to provide an adequate indoor air quality through the building envelope by employing passive ventilating principles and optional active strategies to enhance air exchange rates with acceptable air flow rates.

4.4.2 Identification of exemplary pinnacles (step 2)

"Passive ventilation" is basically to move air from inside to outside, and replace it with fresh air from outside. Thus, air *movement* is the relevant function to be selected from the exploration model (Figure 4.9). The corresponding processes are: (1) *Natural convection*, where a temperature gradient is necessary to perform this process, and (2) *pressure differential*, where velocity gradient and volume variations affect this process. The potential combination of passive and active strategies is relevant for *pressure differential*: *velocity gradient* for passive, and *volume variation* for active. As a consequence, only *pressure differential* is chosen with the corresponding factors and pinnacles.

"Enhance air exchange" is basically to increase the efficiency of air exchange. Thus, air *exchange* is the relevant function to be selected from the exploration model (Figure 4.9). The corresponding process is *diffusion*, where four different factors are indicated. *Surface-volume ratio* is chosen due to its dominance in nature, where *Trachea* is chosen to represent it. *Unidirectional flow* is chosen for efficient flow, where *valves* in veins are representative pinnacle.

In practice, a detailed challenge will filter most of irrelevant pinnacles. A second filtering might then be carried out at the processes/factors level based on available technology, cost estimations, desired materials, or any other limitation of a technical significance. Depending on the size of the remaining relevant pinnacles further (third) filtering might be carried out, based on personal style and selection. Here, since no technical concerns are represented, the final selection of pinnacles, among the relevant ones corresponding to the challenge, was carried out arbitrarily. Figure 4.10, presents the extracted paths from the exploration model relevant for the design challenge.

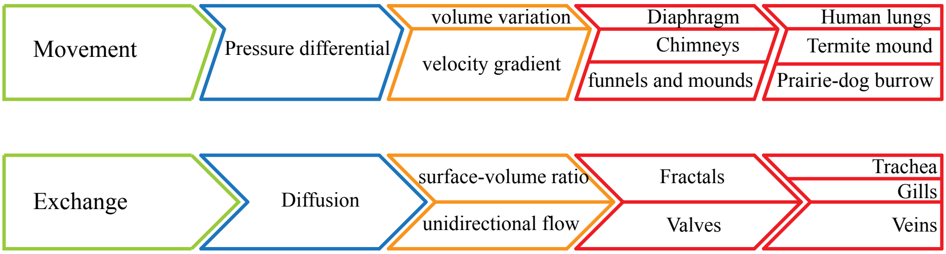


Figure 4.10

The extracted exploration paths.

4.4.3 Analyses of the selected pinnacles (step 3)

The design challenge identified several pinnacles from the exploration model for air regulation: (1) Termite mound, prairie dog burrow, and human lung for air movement, and (2) trachea and valves for air exchange. The pinnacles are explored, based on relevant literature from biology, to outline the different morphological structures and their gas exchange process characteristics for current design challenge. The summary of the analysis is presented in section 4.4.3.1.

Pinnacle 4.1 Termite mounds

Two ways are distinguished for ventilation [Luscher 1961, Korb & Linsenmair 2000]: mounds with chimneys that ventilate according to Bernoulli's principle (Figure 4.11), and mounds with air passages close to the surface without chimneys that ventilate through natural convection. Thus, the mound balances between temperature regulation and ventilation. The reduced surface area in the forest limits gas exchange through the mound, and happens mostly at the crest of the mound [Korb & Linsenmair 2000]. In warmer environments (e.g. Savannah), the surface area is not affected by increasing temperatures. Thus gas exchange occurs through holes all over the surfaces of the mound.

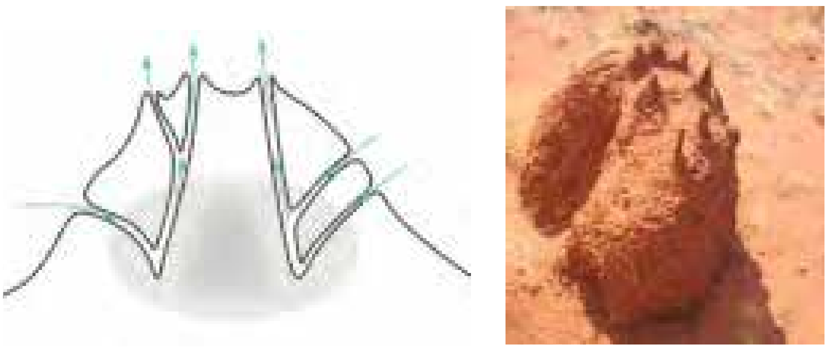


Figure 4.11

Ventilation through chimneys. Left (cross-section): chimneys create lower pressure, thus expel air out, and as a consequence, air is sucked in from the sides. Right: a termite mound with projected chimneys.

Pinnacle 4.2 The Burrow of the Prairie Dog

Prairie dogs occupy arid environments, and prefer areas without vegetation and wind barriers. They live in long and narrow burrows about 12 cm in diameter, 10-30 m long, and 1-5 m deep, with 2-3 entrances [Sheets *et al.* 1971]. Despite the burrow being long and narrow, where diffusion appears to be inadequate, appropriate ventilation is still achieved. Due to this achievement prairie dogs are considered as an extreme case among burrowers [Vogel *et al.* 1973].

The mechanism to achieve this proper ventilation is based on Bernoulli's principle: as the wind flows over the ground's surface a velocity gradient is generated which provides a potential source of work. The prairie dog generates pressure gradients on the ground surface by shaping the two end openings of the burrow one with sharp mound (Figure 4.12, left opening: lower pressure; expels air) and second with a rounded mound (Figure 4.12, right opening: higher pressure; sucks air in)[8].

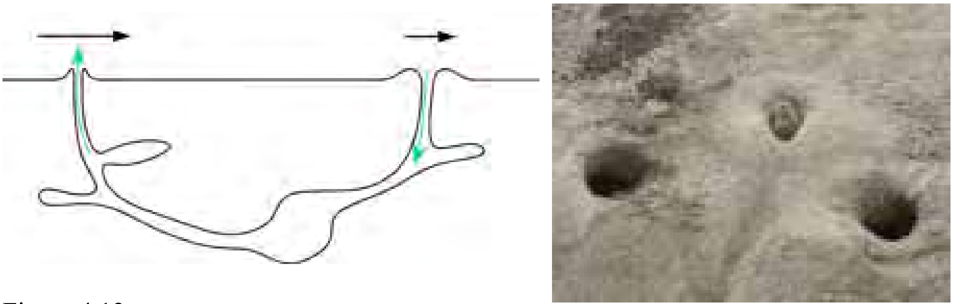


Figure 4.12

Left: cross-section of prairie-dog's burrow showing two openings with different shapes for wind-induced ventilation. The left opening with sharp mound generates higher velocity over surface and results in creating lower pressure, thus expels air out. The right opening with dome mound has lower velocity than the sharp mound and results in higher pressure, thus sucks air in. Right: the different types of openings can be distinguished; the middle representing the sharp mound, and the two openings at the edges representing the dome mound, used with permission, courtesy of Debrester248 [2007].

Pinnacle 4.3 Human Lungs

Two types of lungs can be distinguished: *diffusion lungs* and *ventilation lungs*. *Diffusion lungs* are found in relatively small animals (e.g. snails, scorpions, and some isopods) where gas exchange occurs by diffusion only. *Ventilation lungs* are common in vertebrates, where active pumping of air occurs to create air flow in and out (inhalation and exhalation). A

8 The flow near the surfaces of the mounds follows the geometrical shape of these surfaces (*Coanda effect*), while variations in geometry result in normal acceleration differences, which in turn result in pressure gradient between the two openings.

suction activity causes inhalation, which is aided by muscular contraction (diaphragm), and exhalation follows passively (Figure 4.13). In order to decrease required work for breathing (e.g. muscular activity), many mammals and birds show synchronicity between breathing and locomotion. For example, bats have an exact 1:1 coupling between wing beats and breathing [Carpenter 1986]. The respiratory organ is located inside the body connected to the outside by a pathway. This pathway branches into tree-like structure airways; it consists of 23 generations of airway branching, see Figure 4.14 [Weibel & Gomez 1962]. This branching system ends in small, thin, richly vascularised sacs – the alveoli (around 300 million alveoli). The gas exchange occurs in the alveoli membranes, which have a total of 120-140 m2 surface area for gas exchange. Based on Hess-Murray law, the average diameter of airways in each generation can be predicted [Weibel 2005].

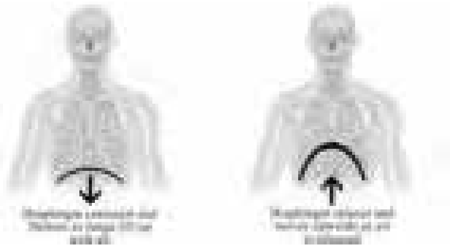


Figure 4.13 ……………………………………………………………………………………..

Left: during inhalation - diaphragm contacts and flattens as the lungs fill up with air. Right: during exhalation - diaphragm relaxes and moves upwards as the air is released. (Skeleton diagram is adapted from [loan-Mihai Gale I, 2012]).

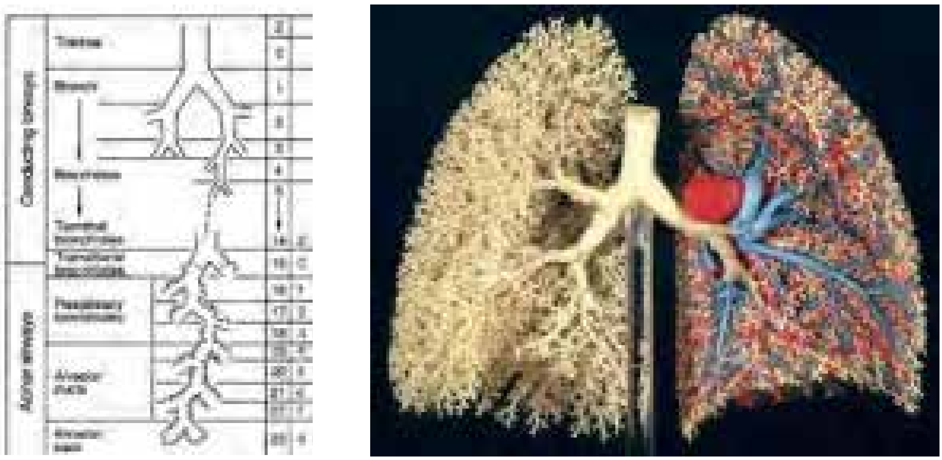


Figure 4.14 ……………………………………………………………………………………..

Left:"*Model of airway branching in human lung by regularised dichotomy from trachea (generation z = 0) to alveolar ducts and sacs (generations 20 to 23).*" Right: "*A resin cast of the human airway tree shows the dichotomous branching of the bronchi from the trachea and the systematic reduction of airway diameter and length with progressive branching.*" [Weibel 2009], Courtesy E.R. Weibel, Institute of Anatomy, University of Berne. Provided and used with permission by E.R. Weibel.

Pinnacle 4.4 Tracheae – fractals efficient gas transport

Tracheal systems are found in all insects and most hexapods. The system is divided into a lot of small tubes that are in a direct contact with muscles and organs. This kind of system functions in bodies less than 5 cm in length. The exchange of gases takes place in the tracheal system only by diffusion, where body movements can increase the diffusion of gases inside. Small pores on the body surface, called spiracles, connect the tracheal system with the atmosphere (see Figure 4.15). Air diffuses through the spiracles into the tracheal system (which branch repeatedly) and reaches all body organs for a direct oxygen supply. The tracheae branch until they end as fine-walled tubules, where oxygen and carbon dioxide can diffuse into and out of the tissues [Mackean 2011]. Gas exchange can be enhanced through conspicuous ventilation (e.g. abdominal pumping and auto-ventilation), and several forms of microscopic ventilation [Hill *et al.* 2008].

The spiracles (up to 12 pairs) are structures that open and close in response to gas exchange requirements. They respond independently to carbon dioxide concentrations, and allow variable amounts of gas to penetrate. Additionally, they have an accurate water loss managing control [Schmidt-Nielsen 2007]. The fine capillaries of the tracheal system do not get filled with water, due to their hydrophobic inner walls which have a contact angle larger than 90° (definition in Figure 4.16). Therefore, the water is forced out of the tubes instead of being pulled in [Denny 1993].

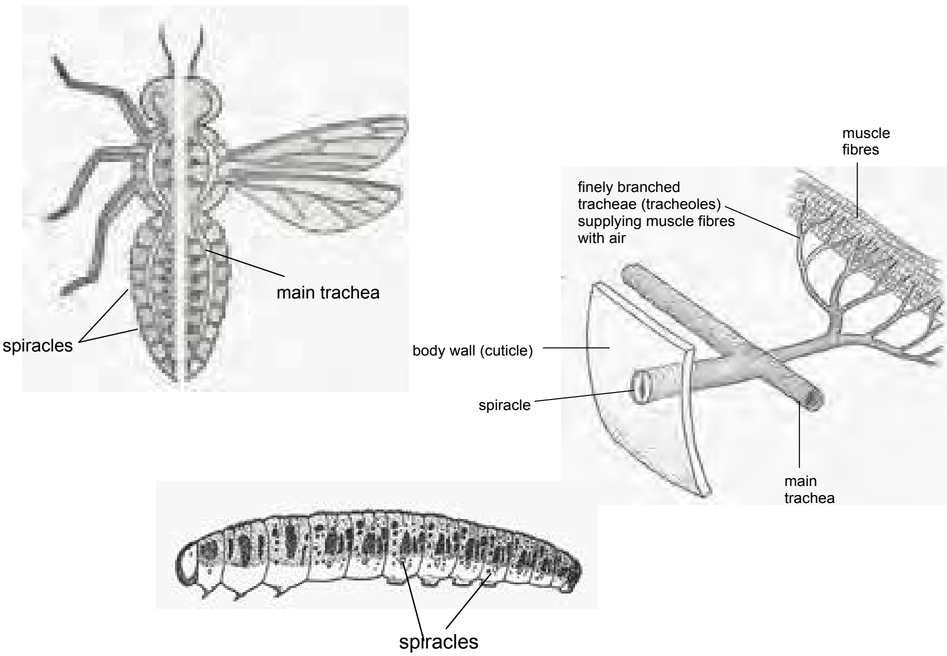


Figure 4.15

Insect breathing system. Top left: diagram of insect tracheal system, right: tracheal supply to muscle tissue, bottom: caterpillar. Reproduced by permission from Mackean [2011], © D.G. Mackean.

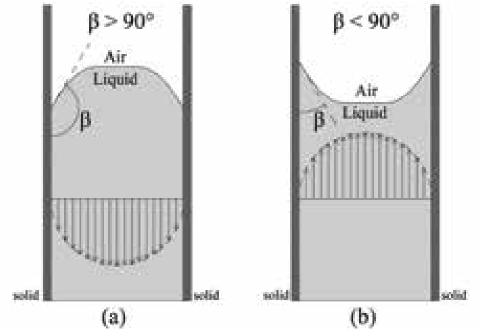


Figure 4.16

Cross section of capillary tube with liquid inside. Contact angle (b) of two different liquids in contact with a solid surface. (a) The capillary force will push the liquid out of the tube. (b) The capillary force will pull the liquid into the tube.

Pinnacle 4.5 **Veins** – unidirectional flow

Veins carry the deoxygenated blood towards the heart. Blood in veins moves under low pressure, where the presence of valves provide unidirectional flow and prevent blood back flow. Valves are elastic membranes, which are attached from one edge to the vein, and free at the other edge to allow full contact when pressure is raised (see Figure 4.17). Thus, preventing back flow of blood in veins.

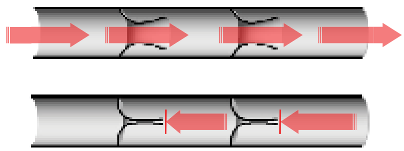


Figure 4.17

Valves prevent blood back flow.

4.4.3.1 Pinnacle analysing

The summary of the analysis of the six pinnacles extracted from the exploration model is presented in Table 4.1, which provides a functional guideline for the design process. Termite mounds, the burrow of the prairie-dog, and human lungs represent some of the mechanisms for gas movement. Trachea represents some of the mechanisms for gas exchange, and veins represent the mechanism for unidirectional flow.

Summary of pinnacles analyses

Table 4.1

Pinnacle's Strategy	Mechanism	Main principle	Main feature
Termite mounds The inhabitants of the mound modify it in accordance to the environmental changes for homeostasis	Structural features to retain or dissipate heat: variations in wall thicknesses, surface pattern, projecting structures, orientation, chimneys, air passages, porosity	Natural convection	Chimneys and air passages
Prairie-dog burrow They build structures with special architectural features to induce air-flow into their long and narrow burrows	They create velocity gradients on the ground surface by shaping the two end openings of the burrow, one with sharp rim and second with a rounded top, which results in inducing the wind through the burrow despite wind flow direction.	*Bernoulli's* principle	Mound and funnel shaped openings
Human lungs Creates volume variations to transfer gas inside and outside the lung. Gas exchange at the thin alveolar walls rich with blood capillaries.	Generating gradient pressure by expansion and contraction to induce gas flow. Systematic reduction of airway size (fractal morphology), thus increase surface area for exchange	Active ventilation	Diaphragm and Fractal structure – *Murray's Law*
Tracheal system in insects Air diffuses through the spiracles into the tracheal system (which branch repeatedly) and reaching all body organs for a direct oxygen supply	Small series of tubes create trachea, where successive reduction in diameter end as fine walled tubules for gas diffusion through the tissues for a direct exchange with organs.	Fractals - system branching based on hierarchy for efficient gas transport via diffusion	Fractals
Veins Unidirectional flow for enhanced exchange	Consist of valves to prevent back flow. The free edge of the elastic membranes attach to each other when raising pressure	Unidirectional flow	Valves

4.4.4 **Design path matrix** (step 4)

In the current example, air exchange and movement are the addressed challenges, see Table 4.2. For each challenge nine categories are presented, e.g., processes, flow, adaptation, scale, etc. The cross signs denote the corresponding features of each pinnacle in each category. The dominant features for gas exchange and movement (separately) are highlighted in red and green (respectively) in Table 4.2, which represent the imaginary pinnacle for each function. In the given example there are three pinnacles for each of the two challenges (i.e., exchange and move). The example provides an illustration for the technique for obtaining the dominant features of each challenge. In that respect, it is notable that increasing the pinnacle sample size would result in more reliable dominant features.

Table 4.2 Pinnacle analysing matrix

Challenges	Pinnacles	Processes: Diffusion	Processes: Natural Convection	Processes: Pressure difference	Flow: Active	Flow: Passive	Adaptation: Physiological	Adaptation: Morphological	Adaptation: Behavioural	Scale: Nano	Scale: Micro	Scale: Meso	Scale: Macro	Environmental context: Arid	Environmental context: Tropical	Environmental context: Moderate	Environmental context: Continental	Environmental context: Polar	Environmental context: Aquatic	Morphological features: Funnels	Morphological features: Mounds	Morphological features: Fractals	Structural features: Valves	Structural features: Chimney	Structural features: Conduits	Structural features: Diaphragm	Material features: Porous	Material features: Elastic	Material features: Conductive	Other features: Counter-current flow	Other features: Contracting	Other features: Expanding	Other features: Unidirectional flow	Other features: Enlarged surface area
Exchange																																		
	Trachea	X				X		X			X			X	X	X	X					X			X									
	Gills	X				X		X			X								X			X								X				X
	Veins	X			X			X			X			X	X	X	X						X					X					X	
	Imaginary pinnacle	X				X		X			X			X	X	X	X					X	X		X			X		X			X	X
Movement																																		
	Termite mound		X	X		X		X				X		X	X									X			X		X					
	Burrow of prairie-dog			X		X		X				X		X		X	X			X	X				X								X	
	Human lungs			X	X				X			X		X	X	X	X	X							X	X		X			X	X		
	Imaginary pinnacle			X		X		X				X		X						X	X				X		X	X	X		X	X	X	

The design path matrix (Figure 4.18) represents the superposition of the imaginary pinnacles for gas exchange and movement challenges in order to determine the dominant features to be addressed in the integrated design concept. The dominant features (the orange nodes) are the features that have the larger number of connections from the different imaginary pinnacles (different path colours), where the larger the number of connections the more dominant the feature becomes.

The design path matrix for air exchange and movement indicates several properties from the various categories relevant for the design concept:

- Diffusion for air exchange, and pressure differential for air movement.
- Passive airflow for both exchange and movement.
- Morphological adaptation influences both functions, which requires attention at the relevant morphological features for each imaginary pinnacle.
- Air movement occurs at the meso scale, and air exchange at the micro scale
- Both imaginary pinnacles share arid environmental context
- Valves and fractals facilitate air exchange
- Conduits and funnel/mound facilitate air movement
- Material elasticity and unidirectional flow are dominant for the material features and other features category, respectively.

The derived dominant features provide guidelines for the design concept. Both imaginary pinnacles share morphological adaptation, but the specific morphological features are not shared. Thus, a physical integration is not recommended for this particular case. Next step (5) illustrates the abstract graphical translation of the design path matrix.

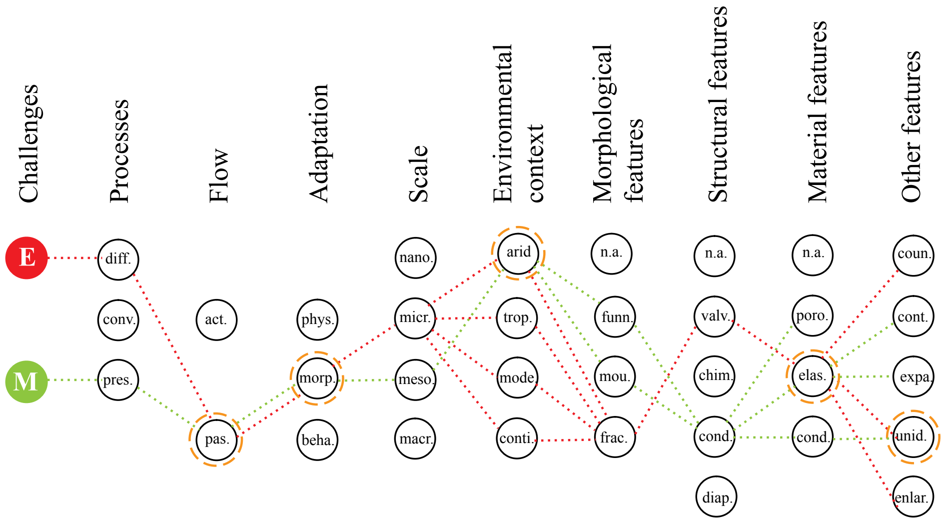


Figure 4.18 ....

Design path matrix. Each vertical column represents a category and its various features. Red lines denote the path of air exchange, the green lines denote the path of air movement, and the orange nodes denote the dominant features which represent the design path.

4.4.5 Preliminary design concept proposal (step 5)

The abstract graphical translation incorporates the various properties extracted from the previous step (section 4.4.4) of pinnacle analysing matrix and design path matrix. A bio-inspired hybrid ventilating envelope should integrate several principles. Here's how it can develop:

Recall the passive ventilating strategy of the burrow of the prairie dog, where mounds over the ground surface generated low pressure. The graphical translation of this for a ventilating envelope based on Bernoulli's principle, where numerous openings project above the roof top and generate low pressure thus expel air out is shown below (Figure 4.19). These openings are connected to air passages with a specific morphology analogical to trachea. The rising warm air (natural convection) inside the space is sucked inside the air passages due to low pressure and is directed outside. The fresh air is introduced inside, at the lower portion of the envelope, through a permeable medium. The permeable medium allows air to diffuse inside passively, and in cases of insufficient air circulation, air pumping chambers located in the permeable medium are activated to generate unidirectional flow.

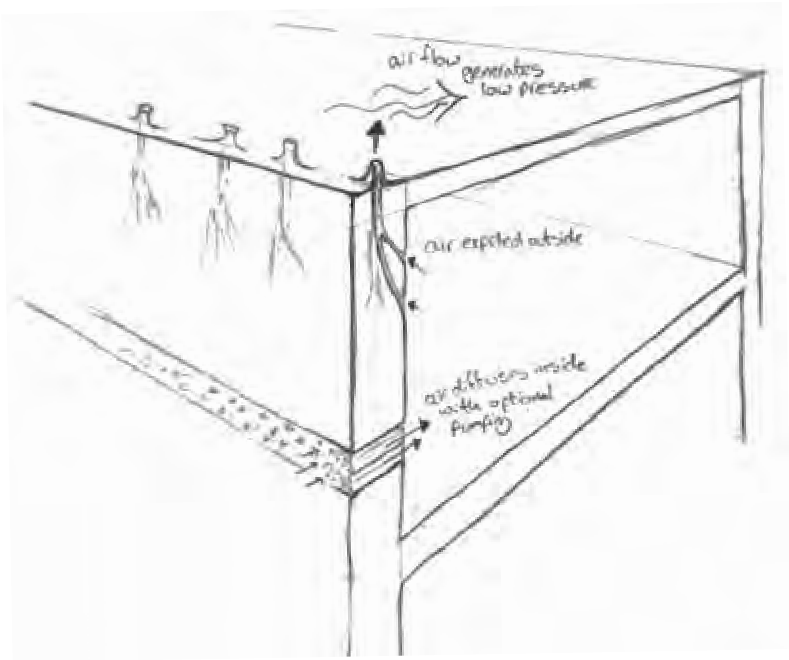


Figure 4.19

A sketch showing the principle of air exchange through the living envelope. Air is expelled outside through numerous chimneys located in the cavity of the envelope, while air is introduced inside through diffusion (at the lower cavity) with optional pumping.

The envelope consists mainly of two parts: a branching chimney to expel air out, and a permeable medium to supply fresh air. The branching chimney has fractal morphology to move air efficiently, see Figure 4.20 a1 & a2. The chimney has four generations of branches with different diameters based on Hess-Murray's law. This morphological configuration will increase the amount of expelled air as a result of the sucking force generated at the upper opening exposed to wind flow. The permeable medium consists of a set of chambers separated by elastic membranes analogical to the diaphragm, and of permeable membranes to allow air flow (Figure 4.20 b1 & b2). The permeable membrane (Figure 4.22), which consists of integrated valves, allows unidirectional flow when the permeable chambers are activated (Figure 4.20 b3 & b4). The three-dimensional illustration of the permeable chambers is presented in Figure 4.21. The diaphragms change from concave to convex and so forth, resulting in expansion/contraction of the permeable chambers (Figure 4.21 a & b). At the expanded state, a low pressure is generated inside the chamber, thus results in sucking air through the outer permeable membranes, where the suction closes the valves of the inner permeable membranes and opens the valves of the outer permeable membranes (Figure 4.21 a). The process is inverted at the contracted state (Figure 4.21 b).

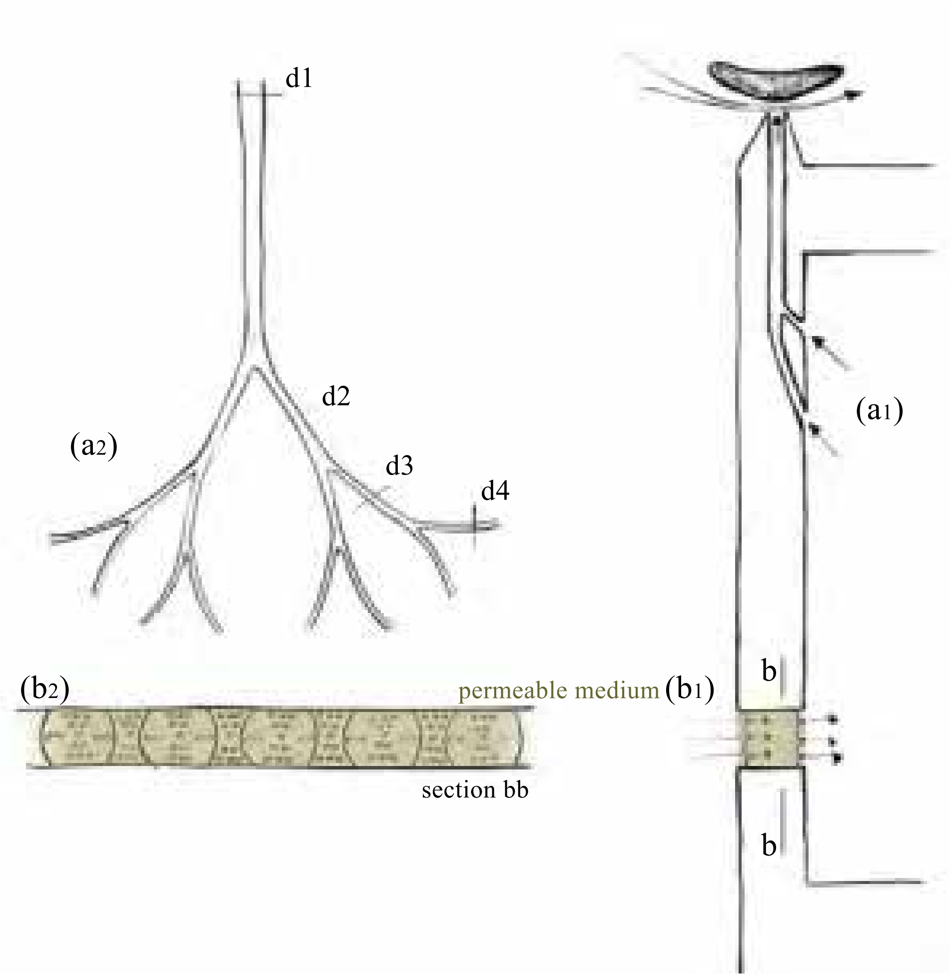


Figure 4.20

Illustrations of the breathing envelope. (a1) the branching chimney with numerous inlets and one outlet, where Bernoulli's principle applies for expelling air. (a2) the chimney has four generations with successive diameters, from d1-d4. (b1) at the relaxed state of the elastic membranes (diaphragms), air infiltrates through the permeable chambers. (b2) section bb: the permeable chambers expanding and contracting, simultaneously.

The permeable membranes are elastic surfaces with integrated little tubes that function similar to the valves in veins. Figure 4.22 demonstrates the possible product result of such membrane concept. It is a continuous surface made of a single material (silicon gel), where pressure differences attract the valves or open them to control air flow.

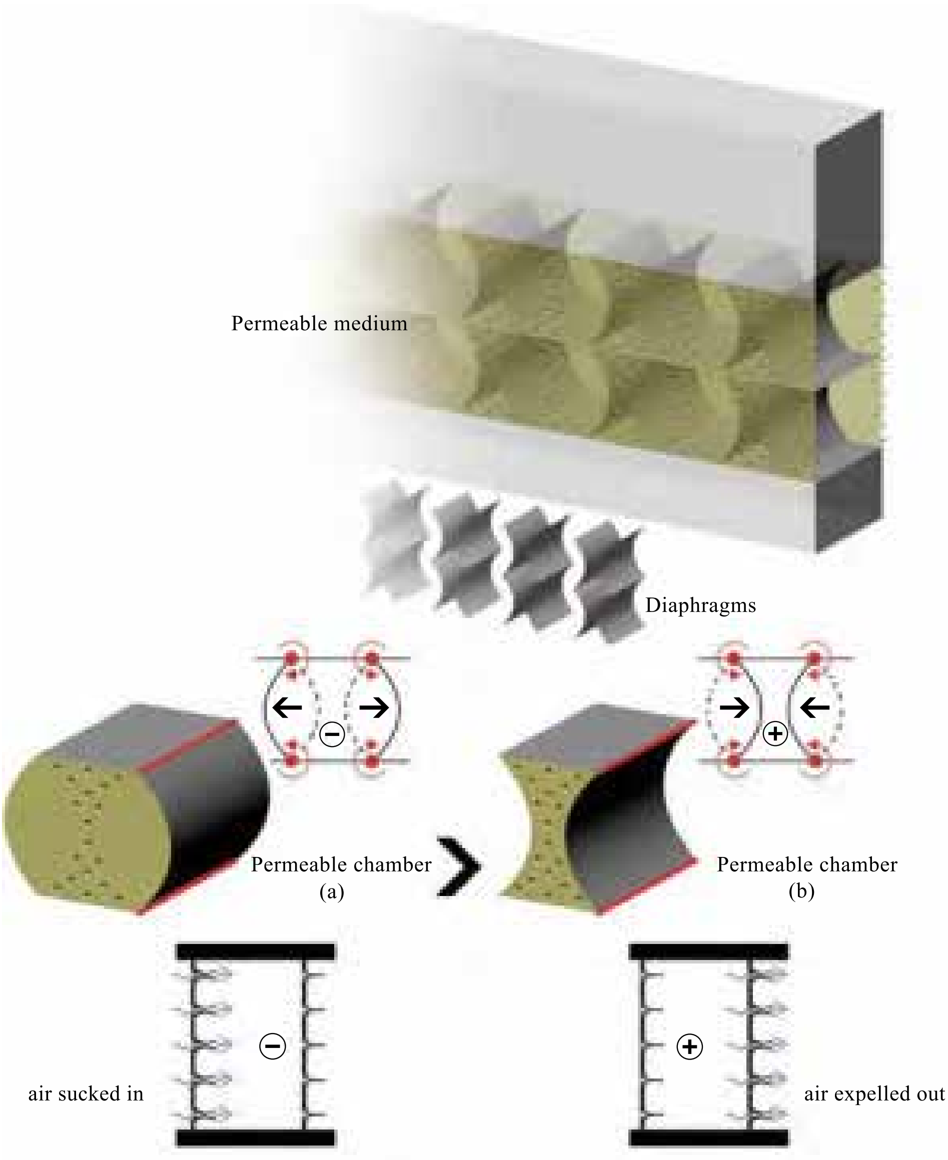


Figure 4.21

Permeable chamber. Air infiltration and active air supply. (a) An expanding chamber results in sucking the air through the outer elastic membrane, and (b) a contracting chamber results in expelling the air through the inner membrane.

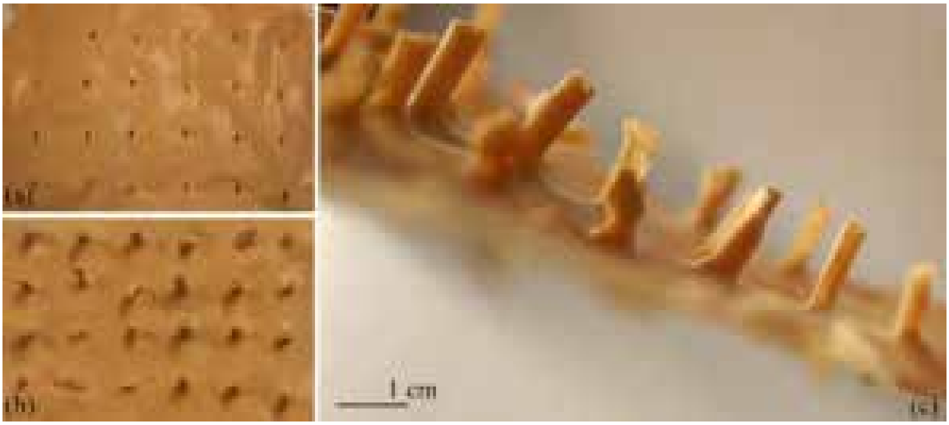


Figure 4.22

Permeable membrane. A surface with integrated valves made of Platsil gel that allows unidirectional flow. (a) The inlet side of the surface. (b) The outlet side of surface showing the integrated tubes, which function as valves. (c) Perspective view on the side with integrated valves.

4.4.6 **Evaluation of performance** – airflow simulations

Airflow simulations have been carried out (originally by [Badarnah *et al.* 2008] for a similar system) in order to evaluate the ventilation performance of the proposed concept design system compared to a standard ventilating system. The simulations were carried out with the solver for indoor airflow modeling Airpak 2.1. In the simulations, permeable chamber (PC) and branching chimney (BC) units were placed only on the (external) front wall of the room, say at the y-z plane where the y-axis is chosen vertical[9].

4.4.6.1 Geometry of Rooms

Two different rooms were considered in the simulations. The first room is a 1 m^3 *testing room* with equal width (x-direction), length (z-direction) and height (y-direction). The second room is a *standard room* with width, length and height being all 3 m. The origin (0,0,0) was placed on the right back bottom corner of the rooms. The components of the simulated ventilating systems, such as the PC or the openings of a standard ventilating system, were placed on the front wall for both rooms, the xz plane.

Configuration of multiple PC and BC units

A total of 14 simulations were carried out. Equal numbers of PC and BC units were considered in all of the simulations. The configuration and number of units for the different cases is shown in Figure 4.23. Each circle represents the inner openings of a single PC, whereas each cross represents the inner openings of a single BC unit. The simulation case 14 represents a standard ventilation system for reference and comparison with other simulations.

9 In the original simulations gravitational forces were neglected and thus orientation of the room is arbitrary.

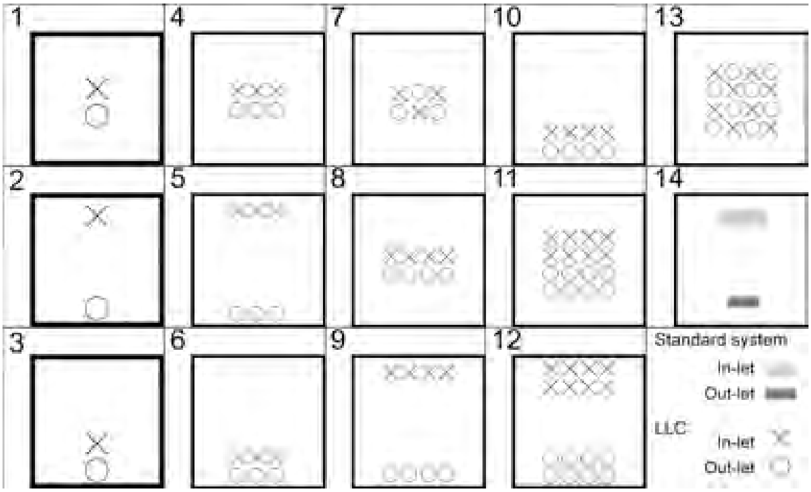


Figure 4.23

Numbers 1-13 present different cases of PC and BC configurations; Number 14 is a scheme of a standard ventilation system.

4.4.6.2 Standard Ventilating System

An additional simulation of the airflow in the standard room with a rectangular ventilating system was carried out for comparison matters. The height of the inlet and outlet is 0.2m and the width is 0.4 m. The inlet has a flow rate of 0.0855 m^3 (equal to the flow rate of cases 11-13). The inlet and outlet were placed in the middle of the front wall at distances 0.2m from the ceiling and floor, respectively.

4.4.6.3 Solution Setup

Grid Spacing

A hexahedron cell has been chosen due to its homogeneity with the rooms. Different types of grid spacing were chosen: 0.01-0.05 m for the testing room; and 0.1-0.3 m for the standard room. The number of elements and nodes of the hexahedron cells are given in Table 4.3.

Approach

The approach that was used to treat turbulence in the rooms is the Reynolds averaged Navier-Stokes equations (RANS). The assumption in this approach is that flow quantities are averaged in time allowing fluctuating quantities from the mean term. These fluctuating terms produce additional turbulence terms that require closure models. Among these models, we chose the zero-equation model and the re-normalization group (RNG) k-e in order to treat turbulence near the openings.

Convergence was reached when the normalized residuals reached below 10^{-3}, and below 10^{-7} for temperature. Details on the computational time and number of iterations for the different cases are presented in Table 4.3.

Summary of the computational parameters of all cases

Table 4.3

Room (m^3)	Airflow rate (m^3/s)	Configuration case (Figure #)	Maximum grid spacing (m)	Number of elements (x10^3)	Number of nodes (x10^3)	Computational time (min)	Number of iterations
1 x 1 x 1	0.0011	1	0.05	141	153	20	85
		2	0.05	162	174	10	70
		3	0.05	146	157	10	80
3 x 3 x 3	0.032	4	0.1	653	685	90	520
		5	0.1	739	775	60	125
		6	0.1	661	694	60	120
		7	0.1	653	685	30	50
	0.0427	8	0.1	817	857	100	185
		9	0.1	951	996	120	160
		10	0.1	885	927	80	120
	0.0855	11	0.3	835	894	45	85
		12	0.3	932	996	45	135
		13	0.3	835	893	30	45
		14	0.3	470	527	30	245

4.4.6.4 Results

Results of the mean age of air (MAA) for the different configurations are presented in Figures 4.24 and 4.25. It is observed, in Figure 4.24, that the MAA is strongly related to the configuration of the PC and BC units. Cases 3, 6 and 10, where the PC's were placed at the bottom of the wall, have the highest MAA compared to the other cases with the same number of PC and BC units. However, larger number of PC and BC units, and thus higher flow rates, doesn't guaranty a lower MAA. As an example, in cases 4 and 8 the flow rates entering the room are, respectively, 0.032 and 0.0427 m^3, even though, the MAA in case 4 is lower than in case 8. The circulation near the inlet, of case 8, causes the fresh air close to the front wall to be expelled through the outlet at higher flow rates than the rates at which air enters further inside the room.

Figure 4.25 compares between two different solutions for cases 11-13. It is notable that the MAA of case 12 is the lowest among all other cases with PC's. However, this doesn't necessarily mean that the distribution of the comfort level of case 12 is the best. In order to evaluate the comfort level of case 12, additional simulation for a standard ventilating system, such as case 14, was considered for comparison matters.

Results of the MAA and flow velocity profiles for cases 12 and 14 are presented in Figures 4.26 and 4.27. In Figure 4.26 it is shown that the MAA of case 12 is higher than case

14, along the chosen line, however, the distribution of the MAA of case 12 is uniform. This means that fresh air is more uniformly distributed in case 12 than in case 14. A possible explanation of this observation is the better mixing produced in case 12 due to the distribution of the inlet openings over larger distances with varied angles of airflow inlet and outlet. As a result, a noticeably lower mean air speed is obtained in case 12 as shown in Figure 4.27.

Figure 4.28 and 4.29 show isolines of the MAA in the (-x) and (-z) planes respectively. The figures compare isolines from case 12 (right subplot), with isolines from case 14 (left subplot). It is also notable, in Figure 4.28, that more isolines of the fresh air, in case 14, are located in the upper part of the room. Apart from this observation, the two plots in Figure 4.28 seem to have similar trend. However, a basic difference is noticed in Figure 4.29 between the isolines of cases 12 and 14. The change in the MAA isolines is diagonal in case 14 (left subplot), whereas vertical in case 12 (right subplot).

Figure 4.30 presents particle trace from the PC units coloured by MAA. The airflow enters the room from the PC inner openings at different angles and moves almost vertically in the middle part of the room.

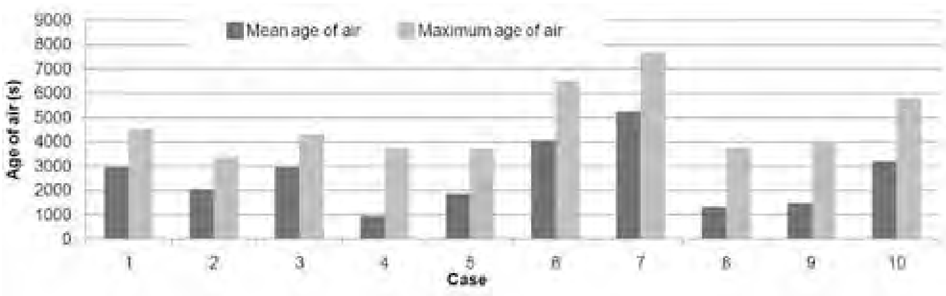


Figure 4.24 ……………………………………………………………………………………..

Mean and maximum age of air for cases 1-10.

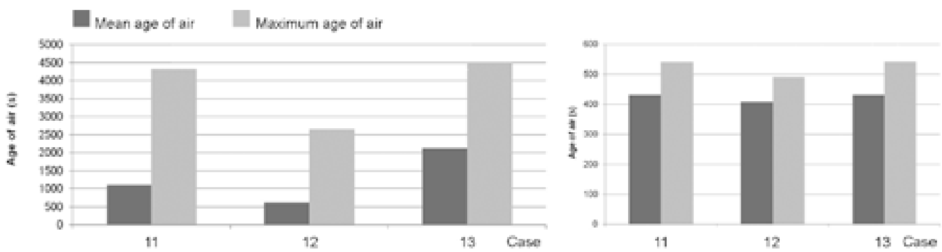


Figure 4.25 ……………………………………………………………………………………..

Mean and maximum age of air for cases 11-13; left: zero-equation; right: RNG with second order discretization schemes.

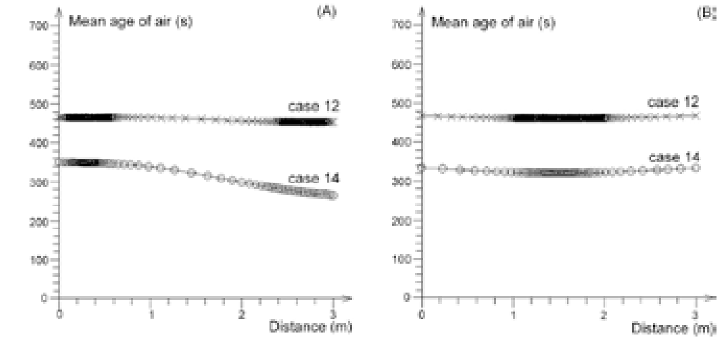


Figure 4.26 ....

Variation of the mean age of air (MAA): (A) along the central vertical line; (B) along the central horizontal line in the z direction.

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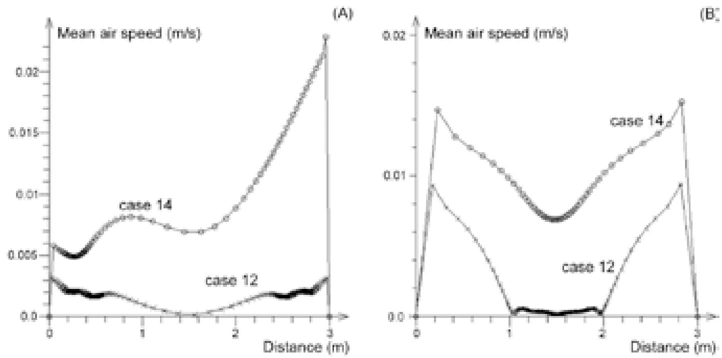

Figure 4.27 ....

Variation of the mean air velocity profiles: (A) along the central vertical line; (B) along the central horizontal line in the *z* direction.

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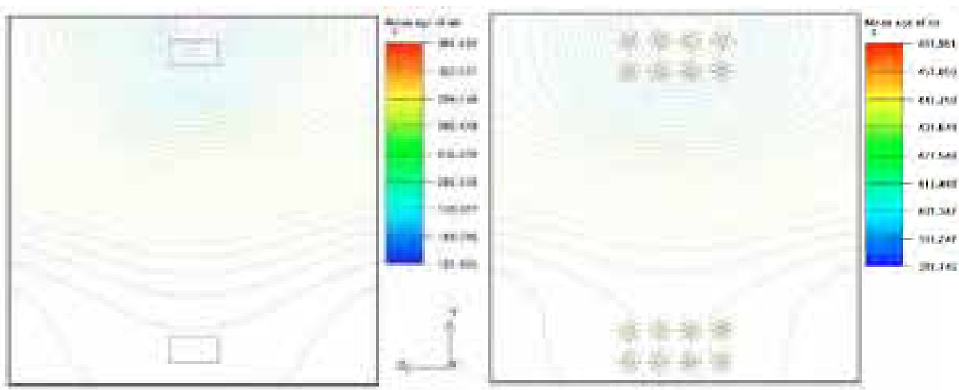

Figure 4.28 ....

Isolines of mean age of air (MAA) in the (-*x*) plane at *x* =2.5 m; left: case 14; right: case 12

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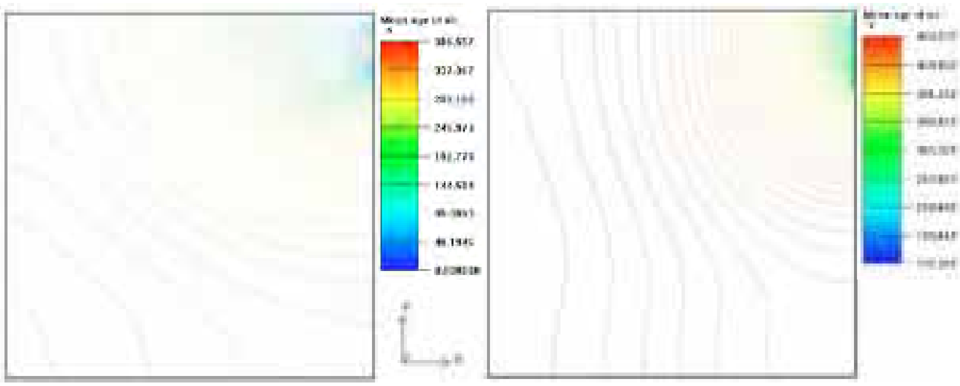

Figure 4.29 ……

Isolines of mean age of air (MAA) in the (-*z*) plane at *z* =1.5 m; left: case 14; right: case 12.

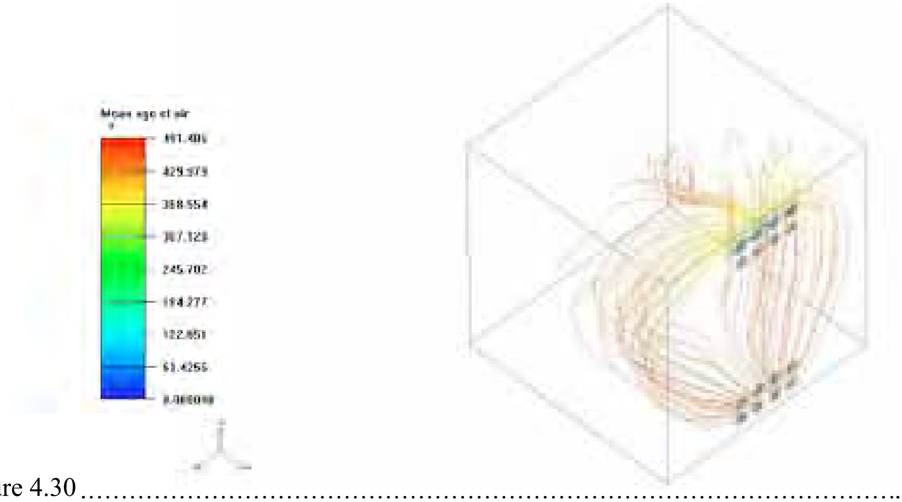

Figure 4.30 ……

Particle trace from the PC openings of case 12, coloured by mean age of air (MAA).

4.4.6.5 Concluding remarks on simulations

Simulations of 13 cases of different configurations, locations and numbers of components in a hybrid ventilating envelope have been carried out. By analysing the MAA, of the different cases, it has been observed that increasing the amount of PC and BC does not guarantee a better distribution of the fresh air. Thus, the location of the different components has a significant effect on the distribution of the fresh air. For example, in case 13 there are almost three times the amount of components found in case 4, however, the MAA of case 13 is only a factor of two times lower.

Among the simulated cases it was found that by increasing the amount of components, a larger distance between the PC and BC is required for effective ventilating. At short distances between the PC and BC, increasing the number of components results in higher rate at which fresh air is being expelled outside before mixing, in this case the component special property of sucking and expelling air at varying angles might become a disadvantage. Whereas, given the 'right' balance between the number of components and the distance separating the inlets and outlets results in a turbulent mixing layer which distributes the fresh air almost homogeneously at each constant horizontal line parallel to the inlet plane.

An interesting result is the fact that when the PC and BC are, respectively, situated at the top and bottom of the wall, the isolines of the MAA show vertical distribution, which is a characteristic property of ventilating systems located at the ceiling.

Furthermore, improving the fresh air quality inside the room could be achieved via standard sliding windows, but the hybrid ventilating system is considered as a ventilating wall, where there is no need to open windows and no requirements for temperature difference during its operation.

In order to further optimise the ventilating envelope for specific operating conditions, the effect of inlet-outlet distance, other configurations and possibly simulations of occupied rooms need to be investigated in more details. Moreover, only the inlet and outlet being at the same wall were considered, whereas it is possible to look at the effect of components distribution on multiple walls. This is left for future work.

4.5 Conclusions

The summary of the investigation of gas regulation in nature presented in the exploration model (section 4.3) is based on four levels: functions, processes, factors, and pinnacles. These levels guide through the decision taking process and lead to the representing pinnacles based on the initial design challenge. The exploration model bridges between available biophysical data on air exchange and movement found in nature, and the objectives of the building envelope in terms of ventilation. Six pinnacles were selected in the exploration model, with the objective to move and exchange air for ventilation purposes. Applying the strategies of these pinnacles in the pinnacle analysing matrix (Table 4.2) and the design path matrix (Figure 4.18) resulted in the main criteria of the generated design concept in a relatively robust manner.

An example for generating a design concept for a ventilating envelope was presented. The envelope transports air outflow through a passive branching chimney system which responses to wind, whereas it transports the inflow through permeable chambers. The latter can perform actively, in case the wind is not strong enough to engage the passive ventilating system. Simulations carried out in a similar system provide an evaluation of the ventilation mixing efficiency. Compared to a standard ventilation system, the proposed design concept is able to achieve similar mean age of air, though it provides better air mixing and movement, as well as lower mean air velocities which can increase occupant comfort. Moreover, the proposed passive system provides ventilation at no energy cost, though it is largely dependent on the outdoor climate.

References

Addington, D.M., [2000]. The history and future of ventilation. In Spengler, J.D., Samet, J.M. and McCarthy, J.F. (eds.), *Indoor Air Quality Handbook*, McGRAW-HILL, pp. 2.1-2.16.

ASHRAE, [2004]. *ASHRAE Standard 62.1-2004: Ventilation for acceptable indoor air quality*. American Society for Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

Badarnah, L. & Knaack, U., [2007]. Bio-Inspired Ventilating System for Building Envelopes. In Proceedings of *the international conference of the 21st Century: Building Stock Activation*, COE Program of Tokyo Metropolitan University, pp. 431-438.

Badarnah, L., Kadri, U., and Knaack, U., [2008]. A bio-inspired ventilating envelope optimized by air-flow simulations. *Proc. of SB08: World Sustainable Building Conf.* 2008, pp. 230-237.

Carey, C., [1980]. Adaptation of the avian egg to high altitude. *Am. Zool.*, **20**, pp. 449-459.

Carpenter, R.E., [1986]. Flight physiology of intermediate-sized fruit bats (Pteropodiae). *J. Exp. Biol*., **120**, pp. 79-103.

Debrester248, [2007]. *Prairie Dog Baby*. Available online at: http://www.flickr.com/photos/debster248/1316482851/ (retrieved February 2012)

Denny, M.W., [1993]. *Air and Water: The Biology and Physics of Life's Media*, Princeton: Princeton University Press.

Gillott, C., [2005]. *Gas Exchange, Entomology*, pp. 469-486, Amsterdam: Springer.

Gould, J.R. & Gould, C.G., [2007]. *Animal architects: building and the evolution of intelligence*, New York: Basic Books.

Hansell, M., [2005]. *Animal Architecture*, New York: Oxford University Press.

Hansell, M., [2007]. *Built by animals: the natural history of animal architecture*, New York: Oxford University Press.

Hess, W.R., [1914]. Das Prinzip des kleinsten Kraftverbrauches im Dienste hämodynamischer Forschung. Archiv für Anatomie und Physiologie. Physiologische Abteilung.

Hill, R.W., Wyse, G.A., and Andreson, M., [2008]. *Animal Physiology*, Massachusetts: Sinauer Associates Inc..

Korb, J. & Linsenmair, K. E., [2000]. Ventilation of termite mounds: new results require a new model. *Behavioral Ecology*, **11**(5), pp. 486-494.

Lavine, S.A., [1964]. *Wonders of animal architecture*, New York: Dodd, Mead & Company.

Liddament, M.W. [1996]. *A Guide to Energy Efficient Ventilation*. Annex V.

Loan-Mihai Gale I [2012]. *Axial skeleton diagram*, available online at: http://commons.wikimedia.org/wiki/File:Axial_skeleton_diagram_ro.svg (retrieved September 2012)

Losa, G.A., Merlini, D., Nonnenmacher, T.F., and Weibel, E.R. (eds.), [2005]. *Fractals in Biology and Medicine*, Vol. IV., Basel: Birkhauser.

Luscher, M., [1961]. Air-conditioned termite nests. *Scientific American*, **205**, pp.138-145.

Mackean, D.G. [2011]. *Insect structure and function 5, Breathing system*. Available online at: (retrieved April 2011).

Maina, J.N., [2002]. *Functional Morphology of the vertebrate respiratory systems*, Enfield: Science publishers, INC.

Mandelbrot, B.B. [1977]. *Fractals: Form, Chance, and Dimension*, San Francisco: W.H. Freeman & Company/Worth Publishers.

McEwen, R.S., Parsons, T.S., Randall, D.J., Clements, L.P., McCutcheon, F.H., Butler, P.J., & McCutcheon, F.H. [2008] Respiratory system, in *AccessScience*, McGraw-Hill Companies, vailable online at: http://www.accessscience.com

Murray, C.D., [1926]. The physiological principle of minimum work applied to the angle of branching of arteries. *J.Gen.Physiol*., **9**, pp. 835-841.

Nave, R. [2012]. HyperPhysics - Georgia State University. *Graham's Law*, available online at: http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/henry.html (retrieved August 2012).

Nicol, J.F., Humphreys, M.A., and Rijal, H., [2008]. Allowing for Thermal Comfort in Free-Running Buildings in the new European Standard EN 15251, Proceedings of *the 29th AIVC Conference in 2008*, Kyoto, Japan, AIVC, 3, 85–90, ISBN 2-9304714-27-1, 14–16 October 2008.

Perino, M., [2009]. Short-term airing by natural ventilation - modeling and control

strategies, *Indoor Air,* **19**, pp. 357–380, doi:10.1111/j.1600-0668.2009.00597.x

Raja, I.A., Nicol, J.F., McCartney, K.J., Humphreys, M.A., [2001]. Thermal comfort: use of controls in naturally ventilated buildings, *Energy and Buildings*, **33**, pp. 235-244

Randall, D.J., [1968], Fish physiology. *Am. Zool.*, **8**, pp. 179-189.

Roulet, C.A., [2008]. Characteristics of mechanical ventilation systems. In Awbi, H.B. (ed.), *Ventilation systems: Design and performance*, pp. 300-344, London: Taylor & Francis.

Schmidt-Nielsen, K. [2007]. *Animal physiology: adaptation and environment*, New York: Cambridge University Press.

Seymour, R.S., Vleck, D., and Vleck, C.M., [1986]. Gas exchange in incubation mounds of megapode birds. *J. Comp. Physiol. B*, **156**, pp.773-782.

Sheets, R.G, Linder, R.L., and Dahlgren, R.B., [1971]. Burrow systems of prairie dogs in South Dakota. *J. Mammal.*, **52**, pp.451-453.

Vogel, S., [1989]. *Life in moving fluids: the physical biology of flow*, New Jersey: Princeton University Press.

Vogel, S., Ellington, C., and Kilgore, D., [1973]. Wind-induced ventilation of the burrow of the prairie-dog,Cynomys ludovicianus. *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology*, **85**(1), pp. 1-14.

Weibel, E.R., [2005]. Mandelbrot's Fractals and the Geometry of Life: A Tribute to Benoît Mandelbrot on his 80th Birthday. *Fractals in biology and medicine*, vol IV, Losa et al. (eds.), Basel: Birkhauser.

Weibel, E.R., [2009]. What makes a good lung?. *Swiss Med Wkly*,**139**(27-28), pp. 375-86.

Weibel, E.R. & Gomez D.M., [1962]. Architecture of the human lung. *Science*, **137**, pp. 577-585.

Heat

Chapter **5**

5.1 Introduction

One of the aims of the building envelope is to maintain thermal comfort in the enclosed spaces occupied by people. Ambient conditions (e.g. air temperature, humidity), ventilation, and solar radiation significantly influence the thermal conditions in a space. These can be influenced both by thermal sources and by the building envelope. Thermal sources, such as radiators, convectors, and air conditioning systems (centralized or decentralized) are normally either attached to the walls, or integrated in the floor or the ceiling, which in general use a great deal of energy and space. The envelope is often considered as a thermal barrier or a shield that has to be insulated to prevent heat loss and allow it to be open to dissipate heat if necessary. Conceiving the envelope in this way limits potentially efficient solutions, where the building envelope is considered as a medium rather than a barrier.

Efficient thermoregulation solutions can be extracted from thermoregulation strategies found in nature, or carried out by living organisms. Living organisms maintain body temperature in very narrow ranges in order to survive. Maintaining a stable body temperature is achieved by a continuous process of heat gain and loss via a wide range of strategies. They can manipulate core temperatures via behavioural or physiological manners and manage it through morphological characteristics. In addition to generating heat metabolically, organisms exchange heat with their surroundings primarily through conduction, convection, evaporation, and thermal radiation [Hill *et al.* 2008]. In some organisms, the process is achieved with the skin functioning as a thermal filter, whereas in others, it is achieved by their built structures. Different mechanisms are adapted for different climates and for different species. The aim of this chapter is to explore and extract thermoregulation mechanisms found in nature, for potential application in building envelopes.

Heat gain, retention, dissipation, and prevention strategies and mechanisms found in nature are presented in section 5.2. The outcome of the investigation is classified in the exploration model in section 5.3. An example of a design concept generation specifically for heat retention is presented in section 5.4. Finally, the concluding remarks are given in section 5.5.

5.2 Thermoregulation in nature

Thermoregulation is the process of keeping inner temperature levels of an organism within certain boundaries (a balance between heat gains and losses) despite changing temperatures in the surrounding environment [Schmidt-Nielsen 2007]. Air temperature, solar radiation, radiation from objects, wind speed, conduction, and convection, can influence body temperature [Stevenson 1985, Tracy & Christian 1986]. Certain ranges of temperatures are required for organisms to perform biological functions. As a result, organisms have adopted physiological, morphological, and/or behavioural means for thermoregulation [Kipervaser 2003].

Behavioural thermoregulation implies a change in an organism's behaviour in response to body temperature changes, where the principal source of the body heat is the environment

[Schmidt-Nielsen 2007]. Cold-blooded animals and ectotherms (poikilotherms) rely on behavioural thermoregulation. Poikilotherms include amphibians, most fish, most reptiles, all aquatic invertebrates, and most terrestrial invertebrates.

On the other hand, the physiological thermoregulation is the process at which an organism regulates its temperature by changing its own physiology [Schmidt-Nielsen 2007]. Thus, the principal source of body heat is generated metabolically.

Organisms utilizing physiological thermoregulation are known as endotherms (homeotherms), which include mammals and birds. Most organisms also use morphological characteristics to supplement physiological and behavioural thermoregulatory strategies. This influences the transfer of heat between animals and their environment by conduction, convection, and radiation [Schmidt-Nielsen 2007].

Through behaviour, physiology and morphology, the body of an organism is in constant balancing processes between heat gain and heat loss. As such, organisms have evolved various strategies for heat gain, retention, dissipation, and loss. The following sections present some of these strategies and their influencing factors.

5.2.1 Heat gain

The sun is the most commonly available external source for radiative heat gain, while metabolic heat production is an internal source of heat gain.

5.2.1.1 Absorb radiation

Insects and reptiles use solar radiation as a source for heat gain. Colour, conductance, distance from a heat source, and orientation (relative to sun) affect their rate of absorption. Dark colours absorb more radiation than bright colours, and many reptiles can change their skin colour by dispersing and contracting dark pigments in their skin [Camargo *et al.* 1999]. Enlarging the exposed area for radiation increases heat gain as well; small organisms gain heat faster than large ones. A proper orientation of body parts towards sun rays, e.g. spreading legs and flattening the body, increases exposed area. Overheating is avoided by changing posture, brightening skin colour, and/or moving into a shaded area [Schmidt-Nielsen 2007]. Even indirectly, solar radiation can be a source of heat gain. For example, cool lizards (e.g. Chuckwalla) come in close contact with a warm rock to increase heat gain via conduction (Figure 5.1).

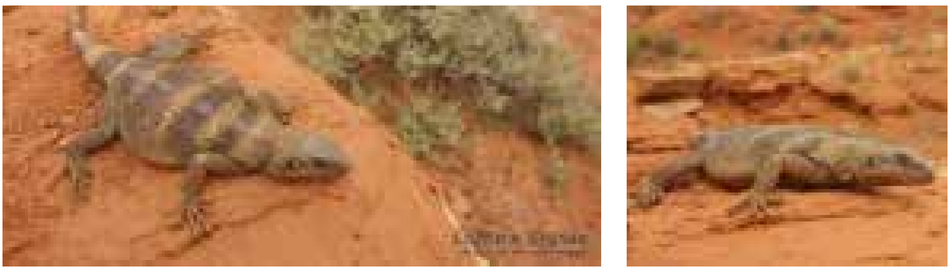

Figure 5.1

The flat body shape of the Chuckwalla allows it to warm rapidly from a rock on a cool morning. Used with permission, courtesy of Cameron Rognan [2010].

5.2.1.2 Increase metabolic rate

An increase in metabolic rate results in increased heat production. This is achieved through muscular activity and exercise, involuntary muscle contractions (shivering), and non-shivering thermogenesis. Heat production through muscular activity and exercise varies by organism and is directly tied to behavioural attributes. Shivering as heat production occurs via two types. The first type is low intensity shivering, where animals shiver at a low level for months during the cold period. The second type is the high intensity shivering, where animals shiver violently for short time during acute needs for heat production. Shivering is more efficient than exercising, since animals stay still and lose less heat to environment via convection. On the other hand, non-shivering thermogenesis results in an increased heat due to the increase in the normal metabolic rate. Non-shivering thermogenesis can be either *facultative*[1] or *obligatory*[2] [Hohtola 2002].

5.2.2 Heat retention

In cold environments maintaining an appropriate *core temperature*[3] is accomplished by insulation, reduced thermal gradient, reduced metabolic rate, and reduced surface area. These strategies can be morphological, physiological, as well as behavioural.

5.2.2.1 Insulation

The level of heat flow from the body to the environment is called conduction. When insulation is high, conduction is low. Fur is primarily for protection and insulation; its thickness may change throughout the seasons to accommodate temperature changes. For example, in the summer the black bear loses 52% of the insulation value of its winter fur [Schmidt-Nielsen 2007]. Birds use multiple strategies for retaining heat. For example, chickadees decrease conductance in the cold by raising their feathers and withdraw head and feet into the feathers (Figure 5.2) (behavioural) [Schmidt-Nielsen 2007]. They trap an insulating layer of air close to the body and in doing so reduce heat losses (morphological). They also allow the peripheral tissues temperature to drop while maintaining the core temperature (physiological). This results in a decreased peripheral circulation, an increased insulation thickness, and enlarged volume. All these contribute in maintaining the core temperature.

Seals and whales that live and swim in the arctic and Antarctic sea have a thick layer of subcutaneous blubber for insulation, since fur loses most of its insulation (i.e. air-trapping) value in water [Scholander *et al.* 1950]. Aquatic mammals modulate heat loss from the skin by blood bypassing the insulation (Figure 5.3) [Meagher *et al.* 2002]. Different body parts are not equally insulated, since animals need surfaces from which heat can be dissipated when required. Different thicknesses of insulating material over the body surface allow a considerable flexibility in regulating conductance (e.g. caribou fur, Figure 5.4) [Scholander *et al.* 1950].

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1 Facultative refers to intended activation to increase body temperature during exposure to cold.

2 Obligatory refers to energy generation due to metabolic rate.

3 Core temperature is the temperature deep within a body.

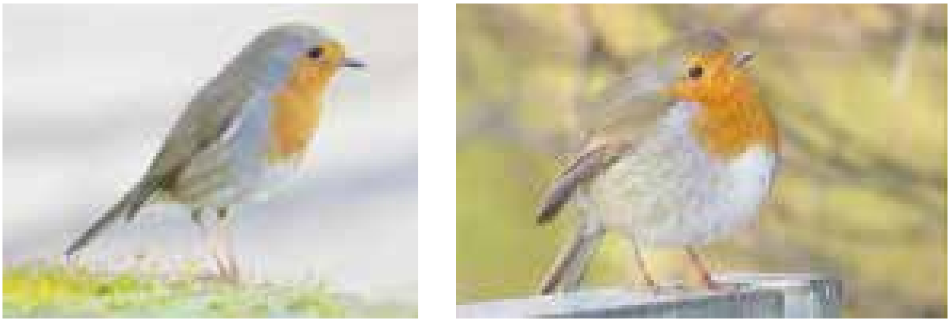


Figure 5.2

Feathers fluff up to decrease conductance. Left: Robin at a normal state. Used with permission, courtesy of Alistair Prentice [2011]. Right: Robin at a fluffed up state. Used with permission, courtesy of Sabineche [2005].

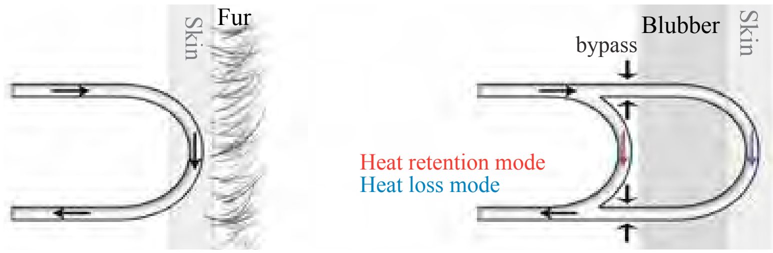
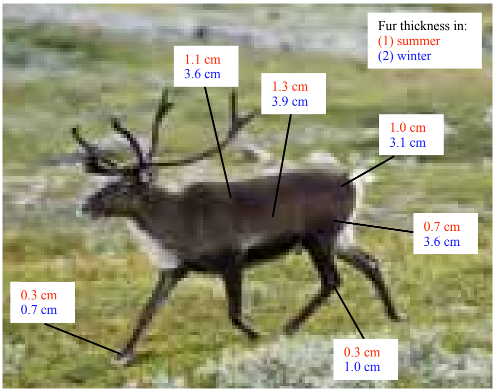


Figure 5.3

Left: fur is located outside the skin surface and can not be bypassed, thus insulation value is not changed. Right: blubber bypass system for enhanced heat dissipation at warm conditions. Scheme after [Schmidt-Nielsen 2007]

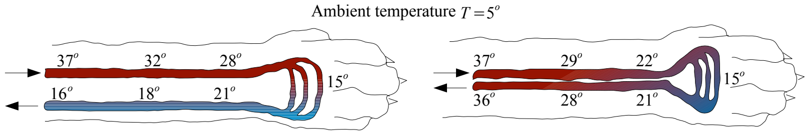
Figure 5.4

Varied fur thickness distribution, and fur thickness difference in winter and summer. Illustration after [Hill *et al.* 2008]



5.2.2.2 Heat exchange

Heat exchange reduces the thermal gradient, thus retaining more heat (Figure 5.5). Heat exchangers are found in many organisms to maintain body temperature in very narrow ranges despite low ambient temperatures, e.g. circulation systems in fish and whales as well as in the tongue of baleen whales [Heyning & Mead 1997]. Heat exchangers can be found in blood vessels with special morphology, e.g. in whale flippers, each artery is completely surrounded by veins. This special structure arrangement results in cooling arterial blood before it reaches the periphery (losing heat to the water), and in warming returning blood (venous blood) before it enters the body core [Schmidt-Nielsen 1972].



(a) Arteries and veins are distant – increased heat loss.

(a) Arteries and veins are adjacent - countercurrent heat exchange

Figure 5.5 Concurrent and counter-current blood flow in dog's feet. Scheme after [Hill *et al.* 2008]

5.2.2.3 Reduce metabolic rate

Reduced metabolic rate leads to a decrease in body temperature, where the temperature difference between body and environment is reduced, thus less heat loss occurs. Some animals undergo hibernation in winter, where they conserve energy when food resources are limited. During hibernation body temperature drops near ambient temperature, heart slows down, and respiration rates are reduced. For example, squirrels manage their temperature set point by reducing their metabolic rate, and consequently decreasing heat generation [Tattersall & Milsom 2003].

5.2.2.4 Reduce surface area – volume ratio

Since heat loss occurs through the surface, a strong relationship exists between heat retention and exposed surface area. Huddling is one means adopted by penguins to reduce collective surface area in the harsh environment of the Antarctic. According to Tributsch, "*the blue whale may have 10 million times the weight of a mouse, but its surface is only 10,000 times as large. Its gigantic size makes it easy for the whale to produce a great deal of body heat; at the same time, it provides efficient protection against excessive heat loss, since the contact surface with the water is relatively small.*", [Tributsch 1984]. Additionally, many animals tuck in extremities like limbs during cold events in order to help with heat retention.

5.2.3 Heat dissipation

In environment where the body temperature is higher than ambient temperature, the body may dissipate heat by convection, conduction, and radiation.

5.2.3.1 Enhance convection

Convection is a major mode for heat transfer where heated fluid (including air) surrounding an object flows away from the object transferring heat. There are two types of convection: (1) natural, where the flow is created by temperature/pressure gradients; and (2) forced, where the flow is generated by mechanical sources. An example of natural convection is heated rising air. Hot air has a lower density than cooler air in the atmosphere, therefore it rises. As it rises, it loses energy and cools down, which make it denser, and thus drops down. This creates a repeating cycle that generates wind. The forced convection involves pumps or any other mechanical force that moves the heated fluid. For example, the flapping movement of elephant ears increases airflow, which enhances convection for heat dissipation. Heat transfer is enhanced by using vibration, where perpendicular vibration to air flow is more efficient than parallel to air flow [Lemlich 1955].

It is argued that the alternating black and white stripes of the zebra have a cooling effect due to the convective currents generates on the surface [Cloudsley-Thompson 1999, Jackson 2012]. In the infrared photo of the zebra (Figure 5.6 right), it is noticed that the temperatures of black stripes are, approximately, 10°C higher than white stripes. The temperature gradient makes the heated air rise and consequently displaced by cooler air, which creates convective currents (Figure 5.6). These currents enhance air flow over the skin and thus increase evaporation rates and result in cooling.

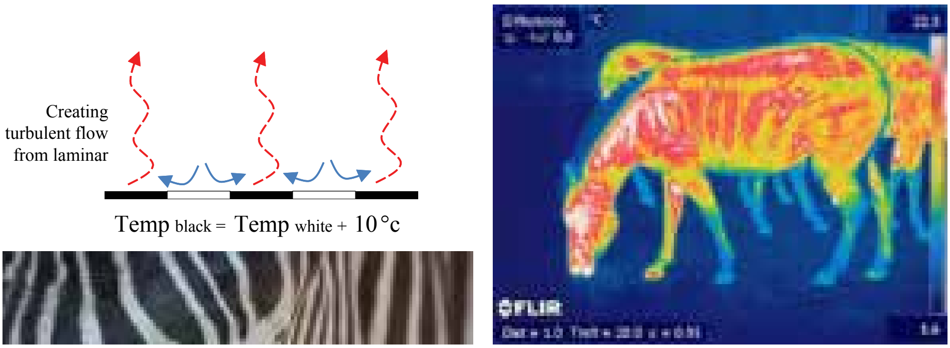


Figure 5.6

Left: alternating black and white stripes of the Zebra create convective currents due to their varied temperatures, thus enhance heat dissipation via evaporation. Right: infrared photo of zebra showing temperature difference of stripes, provided and used by permission from © Steve Lowe.

5.2.3.2 Enhance conduction

Heat conduction is the transfer of heat via direct collisions of particles and kinetic energy transfer at the interface of two matters. Conduction may occur between any combination of solids and fluids. In general, conduction in fluids (especially gases) is less intensive than in solids, though conductivity increases with pressure.

High conductance materials allow heat flow between environment and body. When body temperature is higher than ambient temperature, heat loss is carried out via conduction. Material thickness, density, and surface area affect conduction: (1) the thicker the material the lower the conduction (e.g., blubber – Figure 5.3); (2) the denser the material the higher the conduction; and (3) the larger the surface area the higher the conduction (e.g., wrinkles increase the surface area to volume ratio, which prevents elephants from over-heating – Figure 5.8).

5.2.3.3 Evaporation

When air flows over a moist surface it causes evaporation, which in turn takes a certain amount of heat from the surface. Sweating, panting, and gular fluttering are processes found in different species that increase cooling via evaporation. The capability of sweating is found in some mammals including humans, horses, camels, and some kangaroos. Gular fluttering is a process adapted by some species of birds and lizards in order to increase the rate of evaporative cooling. In this process the animal keeps its mouth open and increases air flow over moist vascular oral membranes by vibration; this in turn increases evaporation and results in increased dissipated heat (Figure 5.7) [Weathers & Schoenbaechler 1976]. Increased heat load results in increased gular fluttering [Bartholomew *et al.* 1968]. Panting is also common among birds and mammals, where the rate of breathing is increased as a result of heat stress, e.g. dogs [Hill *et al.* 2008].

Figure 5.7

A young great egret gular fluttering on a hot day, courtesy of Mike Baird [2009].

5.2.4 Heat prevention

In warm environments with high radiation exposure, it is important to prevent too much heat gain. Organisms prevent heat gain via various strategies, among which are minimizing radiation exposure and minimizing heat load.

5.2.4.1 Minimize radiation exposure

Many desert organisms are primarily active at night in order to avoid the extreme heat

Figure 5.8

Left: wrinkles of elephant skin hold moisture. Right: temperature differences follow the patterns of wrinkles found on elephant skin, courtesy of TService & Arno Vlooswijk (used by permission from Arno Vlooswijk).

of the day. Sometimes the tendency to dissipate heat may create conflicts with heat prevention. For example, providing large surfaces for evaporation may result in large surfaces for heat gain. As a result, some morphological adaptations are distinguished among organisms to minimize heat gain and exposure to radiation. Wrinkles on the surfaces of the skin are one of the means for less radiation exposure by creating shaded regions, which provides a sufficient area for holding moisture and evaporation yet prevents too much direct exposure (Figure 5.8) [Lillywhite & Stein 1987].

5.2.4.2 Minimize heat load

Since heat gain of an object by conduction, convection, and radiation processes has a direct relation to surface characteristics, the sum of environmental heat load on an object is directly related to surface area. A large volume/surface ratio prevents too much heat gain, e.g. elephants. Camels and other large volume animals inhabiting warm climates are less likely to absorb too much heat due to, among other factors, their smaller surface area to volume ratio (compared to small animals, larger animals have proportionately less body surface in contact with the environment - Gigantothermy).

Surface colour and reflectance level have a great impact on radiation absorption. In mammals and birds, skin colour, and hair or feather optics are important factors for solar heat gain [Walsberg *et al.* 1978, Walsberg 1983, 1988a]. The surface colour is mainly due to pigmentation, though structures formed on the surface (e.g. of a leaf or fur) may increase reflectance, and thus modify the original colour to become lighter, i.e., silver, white, gray, copper, blue, or gold [Gibson 2012]. Examples: (1) the highly reflecting scales of Skink helps reducing heat load, and the fur structure of the rock squirrel results in a minimized solar heat gain [Walsberg 1988b]; (2) the desert brittlebush has reflecting silvery leaves, that reduce the surface temperature by several degrees [Gibson 2012]; (3) some plant leaves have highly reflective leaves to lower leaf temperature in hot summer days (e.g. saltbush), while others (e.g., ramie and senecio) have dense reflection structure only on the lower leaf surface (the hypothesis is that these prevent radiation reflection from the ground) [Gibson 2012].

5.3 Exploration model for heat regulation

The investigation and exploration of heat regulation in nature is based on four initial functions: gain, retain, dissipate, and prevent (see Figure 5.9). Each function incorporates different processes. Note that some of the processes were indicated in the exploration model for air regulation (Figure 4.9). The exploration model is classified based on four levels. On the first level the functional aspects are identified, e.g. heat gain. The second level of exploration distinguishes the processes that manipulate the identified functional aspects, e.g. absorb radiation. The influential factors affecting the distinguished processes are explored on the third level, e.g. exposure area. These factors lead to the fourth level of exploration, where pinnacles represent a particular function, e.g. Chuckwalla for heat gain. The content of the presented model is a representative state for the current exploration, where it can be extended and new entities at the various levels may be added in future elaborations. The systematic representation of entities and their relationships support the access to relevant information, which is further discussed in the following section by an example.

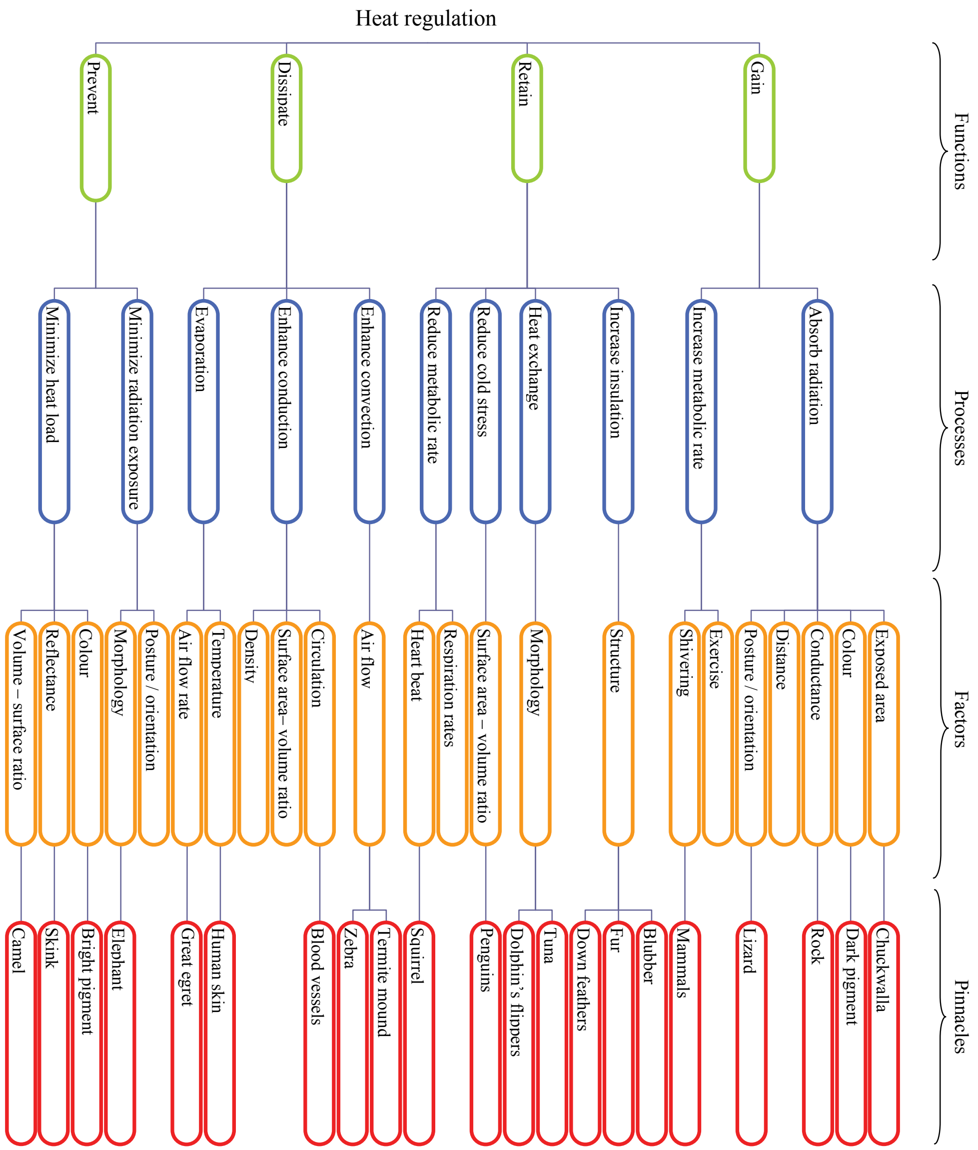


Figure 5.9 ....

Exploration model for heat regulation.
....

5.4 Example: heat regulation system

Buildings in developed countries consume approximately 40% of the overall energy use, where almost half of it is for heating, ventilation, and air-conditioning (HVAC) systems [Pérez-Lombard *et al.* 2008]. In order to reduce energy demands in buildings we have to develop more energy efficient services and technologies. The common use of insulation in building envelopes and improving air-tightness significantly reduces the required heating and cooling, which results in reduced energy consumption. However, these insulations create barriers between the environment and the occupied spaces, and result in reduced indoor air quality that decreases occupant satisfaction [Taylor & Imbabi 1998]. This suggests that *air infiltration*[4] through the building envelope is important for occupant satisfaction. The search for alternative design concepts for building envelopes, which allow air infiltration while retaining heat, might be beneficial for energy efficiency and occupant comfort. The following sections demonstrate an example for generating such a design concept. The steps of the concept generation are based on the methodology presented in chapter 3.

5.4.1 **Definition of the design challenges** (step 1)

The challenge defined for the current design is to reduce energy loss for heating and increase cooling efficiency by dissipating heat excess.

5.4.2 **Identification of exemplary pinnacles** (step 2)

"Reduce energy loss" for heating is analogous to heat retention from the exploration model, where organisms decrease heat loss via physiological, morphological, and behavioural means in order to maintain body temperature in an acceptable range. The corresponding processes are (see Figure 5.10): (1) increase insulation, where structure influences the conductance of a particular material, and the representative pinnacles are blubber, fur, and down feather. For the matter of design process only down feather was selected as a representative pinnacle. (2) Counter-current flow, where morphology has a direct impact on heat exchange, and the representative pinnacle is dolphin's flippers. (3) Reduce cold stress, where surface-volume ratio is a significant factor. Penguins are selected as the representative pinnacle. The process of reduce metabolic rate is analogous to reducing internal heat loads (such as people, computers, and other electric devices), which is not the intention of the current design concept.

"Increase cooling efficiency by dissipating heat excess" is basically analogous to heat dissipation from the exploration model, where organisms increase heat loss via physiological, morphological, and behavioural means. The corresponding processes are (see Figure 5.10): (1) enhance convection with representative pinnacle termite mound. (2) Enhance conduction with representative pinnacle blood vessels. For the matter of the design process, current design challenge doesn't intend to incorporate water, thus evaporation was not selected.

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4 "Air infiltration is a term that describes the uncontrolled air movement through cracks, gaps and openings in the envelope of a building, driven by wind pressure and the stack effect" [Air infiltration 2009]

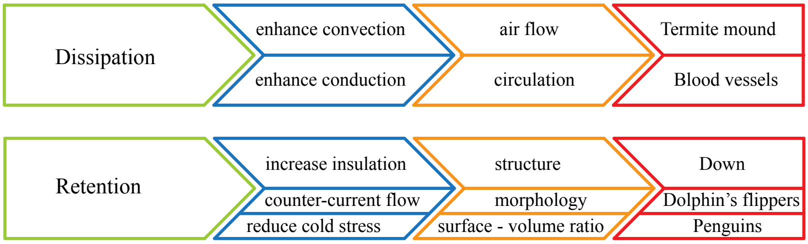

Figure 5.10

The extracted exploration paths.

5.4.3 Analyses of the selected pinnacles (step 3)

The thermoregulatory strategies of the selected pinnacles, down, dolphin's flippers, penguins, termite mound, and blood vessels, are investigated and analysed in the current section, and summarized in section 5.4.3.1.

Pinnacle 5.1 Down (Penguin's feather)

The down (have similar function to afterfeather) is a layer of fine and short barbs and barbules that lack hooks (Figure 5.11), which provides insulation. The tiny, fine, and fluffy morphology of the down provides an excellent thermoregulation characteristic: the loose structure traps air bubbles, which decrease heat loss [Du *et al.* 2007], by slowing convection and conduction.

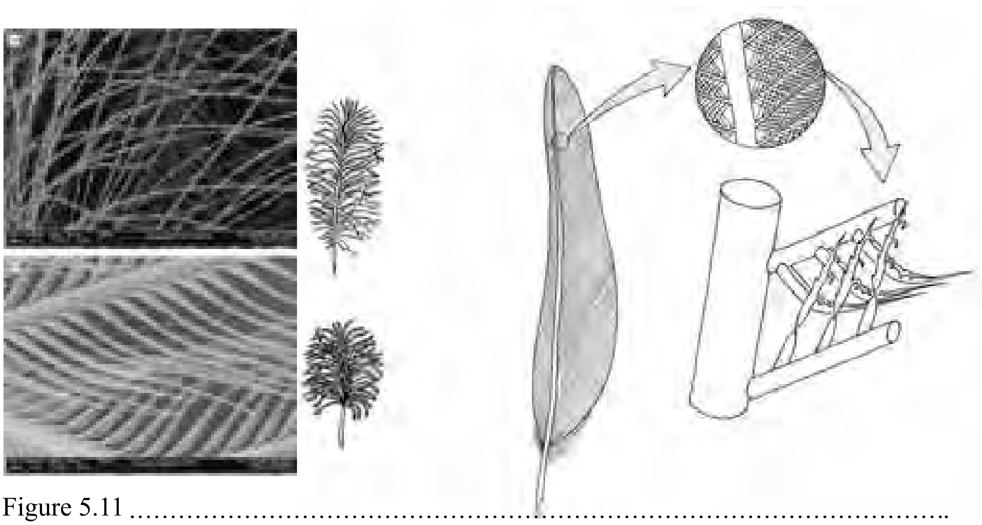

Figure 5.11

Left: "*scanning electron photomicrographs of downy (top) and pennaceous (bottom) barbules of an American Crow (Corvus brachyrhynchos).*", reprinted from [Dove *et al.* 2007], Copyright © 2007, with permission from Elsevier. Right: "*Bird feathers consist of a shaft with rows of fine filaments (barbs) on each side. The barbs themselves have finer filaments (barbules) branching from them. In the down feathers, the barbs and barbules are loose and fluffy.*", adapted from [Mackean 2012], Copyright © DG Mackean (used with permission).

According to Dawson *et al.* [1999], in penguins, "*the function of the cilia*[5] *is, most probably, to entangle one another and allow the barbules to move in only one direction relative to one another via a "stick slip" mechanism.*", "*The net effect of the arrangement of the barbules is to produce a regular, uniform division of the air space within the coat with well defined dimensions*", see Figure 5.12c.

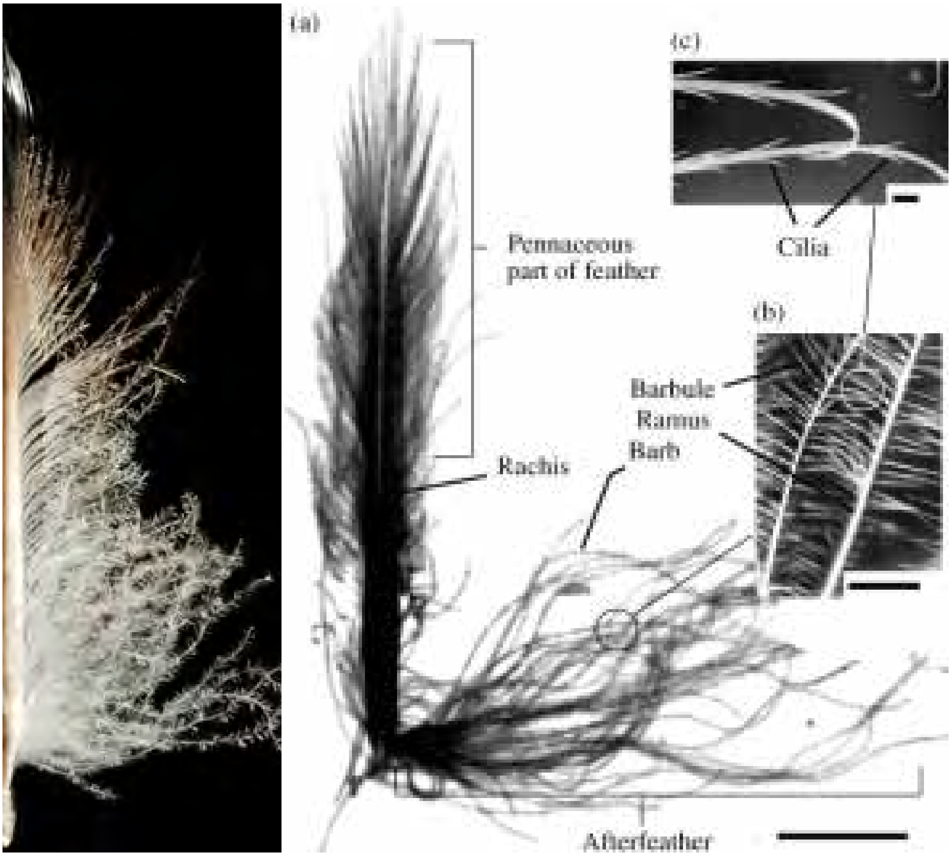

Figure 5.12

Left: penguin feather- large shaft and lots of down, courtesy of Featherfolio [2008]. Right: " (a) Image of a penguin (Pygoscelis papua) feather including afterfeather (scale bar, 5 mm). (b) Optical micrograph of barbs from the afterfeather (scale bar, 500 µm). (c) Scanning electron micrograph of barbules (scale bar, 10 µm).", reprinted from [Dawson *et al.* 1999], Copyright © 1999, with permission from Elsevier.

5 "*The cilia may be functionally equivalent to nodes on the barbules of downy feathers in ducks but the shape is very different – hence the different name. They increase in number and length towards the tip of the barbule and are 25-30 µm long at the tip of the barbule. They project at an acute angle to the barbule.*" [Dawson *et al.* 1999]

Pinnacle 5.2 Dolphin's flippers

Dolphin's flippers lack blubber using a vascular counter-current heat exchange to maintain a stable temperature. The veins that carry the cool blood back to the body run along the arteries that carry the warm blood from the body at the periphery [Scholander & Schevill 1955]. By this special arrangement, arterial blood reaching the periphery is cooled down to ambient temperature, thus heat loss is reduced (Figure 5.13). By cooling the surface, the thermal gradient (surface, body, and water) is reduced, resulting in improved heat conservation [Carey & Teal 1966]. Cold blood going back to body is warmed up gradually by gaining heat from the adjacent artery, and ensuring the blood is at core body temperature when reaching the trunk. A dolphin may dissipate heat if necessary by increasing blood circulation to the veins near the skin's surface [Kvadsheim & Folkow 1997].

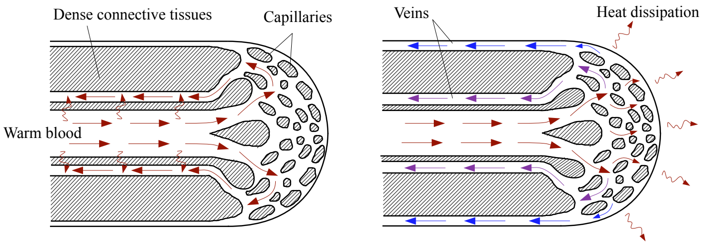

Figure 5.13
Blood circulation for heat retention and dissipation in flippers. After [Coturnix 2006].

Pinnacle 5.3 Penguins

Penguins live in the coldest environment of Antarctica, where air temperatures may reach -40°C and wind speed 144 km/h, yet they are able to maintain a core body temperature at 38°C. Several adaptations for survival include: short and dense stiff feathers, downy filaments between feathers and skin, up to 3cm thick fat layer, reduced metabolic rate, movements and shivering, and huddling [Schmidt-Nielsen 2007].

The last strategy, huddling, is a complex social behaviour that enables the penguins to maintain a high body temperature despite very low ambient temperatures. During huddling they pack themselves so tightly with a coordinated movement, see Figure 5.14 [Zitterbart *et al.* 2011]. The packing structure is continuously reorganised to allow penguins at the periphery to get enough time inside the cluster, which can reach as much as 37.5°C [Gilbert *et al.* 2007]. By huddling, they reduce the total exposed surface area to the cold wind, thus reduce heat loss, while also utilizing any ambient heat loss of neighbours.

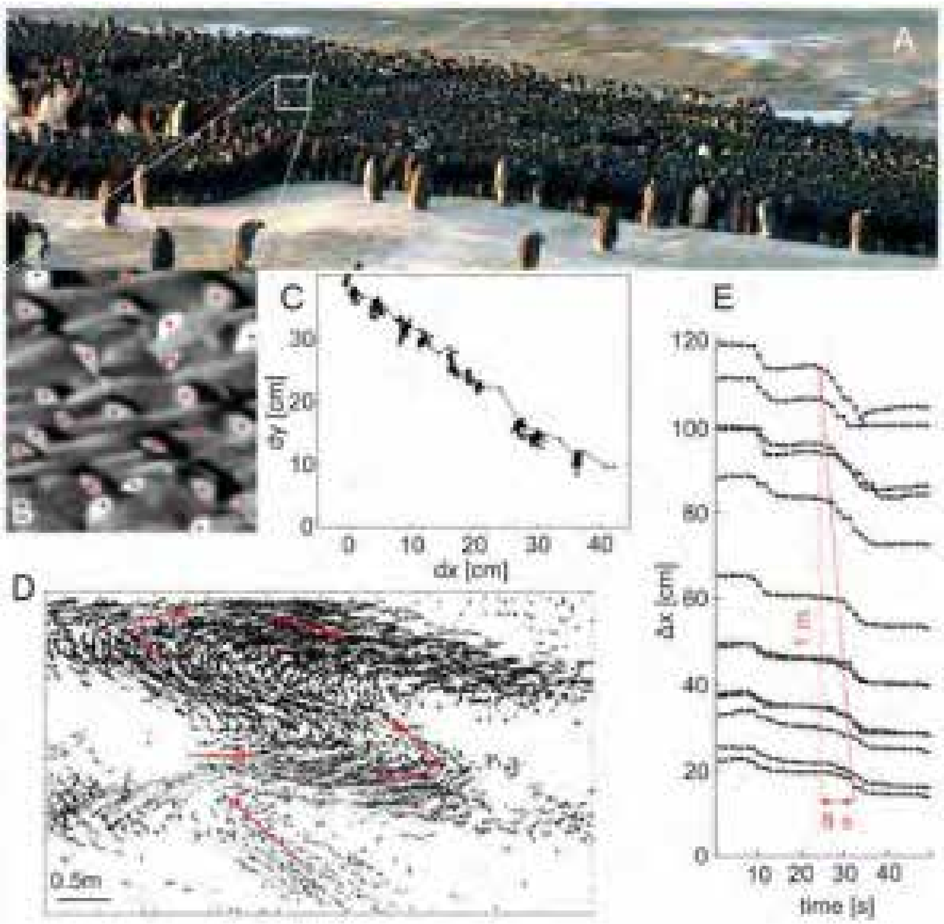

Figure 5.14

Huddling. “Emperor penguins move collectively in a highly coordinated manner to ensure mobility while at the same time keeping the huddle packed. Every 30-60 seconds, all penguins make small steps that travel as a wave through the entire huddle. Over time, these small movements lead to large-scale reorganization of the huddle”. Adapted from [Zitterbart *et al.* 2011], with permission from PLOS one.

Pinnacle 5.4 Termite mounds

Termite mounds can maintain a steady internal temperature of around 30°C despite the temperature variations occurring throughout the day, 12°C (night) ~ 40°C (day) [Korb 1998]. The structural features of the mounds allow heat dissipation and retention, for example: variation in wall thicknesses, mound surface design or projecting structures, and orientation [Jones & Oldroyd 2006]. Mounds found in the savannah biome (warm environment) have thin walls with numerous ridges and turrets (enlarged surface area), which results in more heat dissipation in the savannah mounds [Korb & Linsenmair

1998, 1999]. The mounds (Figure 5.15) have air passages close to the surface without chimneys that ventilate through natural convection [Luscher 1961, Korb & Linsenmair 2000]. Thus, the mound balances between temperature regulation and ventilation. In warm environments, the surface area is not affected by increasing temperatures. Thus gas exchange occurs through holes all over the surfaces of the mound [Korb & Linsenmair 2000].

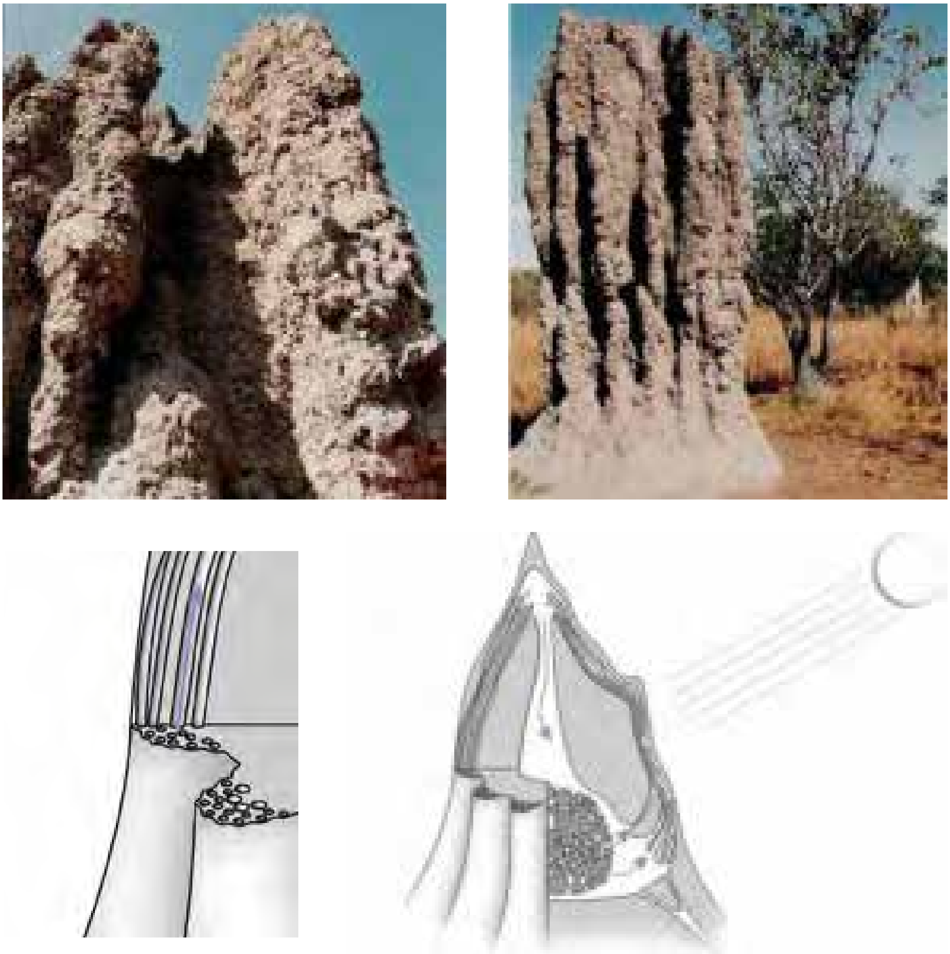

Figure 5.15

Ventilation through the porous surface of the mound. Top: (left) Cathedral mound close up showing the rough surface of the ridges (right) Cathedral mound. Photographs provided by Karen Sullivan. Bottom: (left) section through the ridges of the mound showing the fine peripheral channels close to surface for ventilation. (right) cross section (combined vertical and horizontal) through the mound showing the airflow inside the mound induced by external radiation.

Pinnacle 5.5 Blood vessels (Human skin)

The skin provides a medium between the organism and the surrounding environment, which controls heat and moisture transfer in response to thermoregulatory demands of the body. It contains cold and warm sensors, where the cold sensors are closer to the surface [Hensel 1982], and count ten times more in amount than the warm sensors [Guyton &Hall 2000]. This organisation allows a rapid detection of cold than warmth [Arens & Zhang 2006], which suggests that humans are more sensitive to danger from cold than from heat.

Thermoregulation by vasoconstriction or vasodilatation reduces or enhances (respectively) blood circulation to the skin surface. This process promotes heat loss by conduction to the surrounding with vasodilatation, and prevents heat loss in the cold with vasoconstriction, Figure 5.16. A dense vascular network (the venous plexus) in the subcutaneous region has a major effect on skin temperature and heat transfer from the skin to the surrounding environment. When arterio-venous anastamoses (valves) are open, they provide a shortcut for the blood route from the arterioles to the venous plexus, which act as a warm chamber next to the skin surface, resulting in heat loss via conduction to the environment [Arens & Zhang 2006].

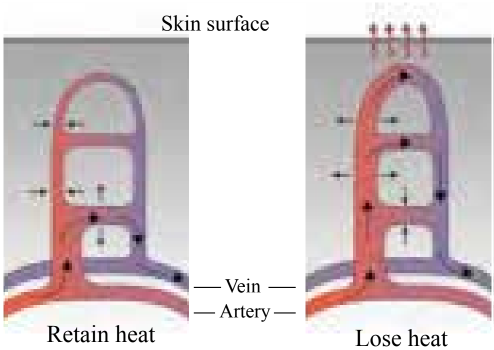

Figure 5.16

Vasodilatation and vasoconstriction- smooth muscles in the arteriole walls allowing differentiation in the amount of blood flow. Scheme after [Biology blog 2009].

5.4.3.1 Pinnacle analysing

The summary of the pinnacle analysis is presented in Table 5.1, which provides a functional guideline throughout the design process. Down, dolphin's flippers, and penguins represent some of the mechanisms for heat retention, and blood vessels for heat dissipation.

Summary of pinnacles analyses.

Table 5.1

Pinnacle's Strategy	Mechanism	Main principles	Main feature
***Down** (bird's feathers)* Special morphological arrangement of the feather to decrease heat conduction	The barbs and barbules are fine and lack hooks, which compose a fluffy morphology. This special morphology of the down traps air pockets close to the skin surface	Trap air pocket to decrease conduction	Low conduction
Dolphin's flippers Reducing thermal gradient (body-environment) to improve heat conservation. This is done by vascular heat exchangers	Blood vessels that supply the flippers run in opposite direction with the returning blood from the periphery. The blood gradually warms up and cools down to prevent heat loss	Flow in opposite direction to conserve heat	Counter-current heat exchange
Penguins Huddle together to reduce cold stress	By huddling, penguins create a warm micro climate in the cluster and reduce surface area in contact with the very cold air	Reduce surface area – volume ratio for less heat loss	Reduced surface area
Termite mounds Heat dissipation with enhanced air flow and ventilation	The increased surface area of the mound allows more radiation, which enhances air flow in the peripheral channels, thus enhance convection	Increase air flow near surface for ventilation and cooling by enhanced convection	Enhance convection
Blood vessels Regulate blood circulation close to the skin surface to increase/decrease heat dissipation	Regulating heat conductance of the skin by dilating/constricting blood vessels and enhance blood flow amount in the vessels	Alter flow amount for increased/decreased dissipation	Vasoconstriction & vasodilatation

5.4.4 Design path matrix (step 4)

Heat retention and dissipation are the addressed challenges for the design concept generation. For each challenge nine categories are presented (Table 5.2), and the cross signs denote the corresponding feature of each pinnacle in each category. The dominant features for heat retention and dissipation (separately) are highlighted in the green box and the blue box (respectively) in Table 5.2, which represent the imaginary pinnacle for each challenge. Note that for the heat retention challenge, some categories did not result in dominant features (i.e. "processes", "adaptation" and "environmental context"), which implies that the pinnacle sample size is not large enough. In more complicated detailed cases where larger number of categories is required, it is advised to increase the pinnacle sample size in order to obtain dominant features in the overwhelming majority of the categories. Having less dominant features increase possible feature combinations, thus a design concept generation is subject to the chosen features.

Pinnacle analysing matrix.

Table 5.2

		Processes					**Flow**		**Adaptation**			**Scale**				**Environmental context**						**Morphological features**							**Material features**		**Other features**			
Challenge	**Pinnacles**	Increase insulation	Counter current flow	Reduce cold stress	Enhance convection	Enhance conduction	Active	Passive	Physiological	Morphological	Behavioural	Nano	Micro	Meso	Macro	Arid	Tropical	Moderate	Continental	Polar	Aquatic	Modular & Compact	Filaments	Adjacent	Branching	Fluffy	Conduits	Cluster	Conductive	Elastic	Peripheral flow	Reducing surface area	Unidirectional flow	Enlarged surface area
Retention																																		
	Down feathers	X						X		X	X			X					X	X			X			X		X				X		
	Dolphin's flippers		X					X		X			X						X		X			X			X		X	X			X	
	Penguins			X			X				X			X						X		X		X				X	X			X		
	Imaginary pinnacle	X	X	X				X		X	X			X					X	X				X				X	X			X		
Dissipation																																		
	Termite mound				X			X		X				X		X	X								X		X				X		X	X
	Blood vessels					X		X	X	X			X			X	X	X	X	X					X		X		X	X	X		X	X
	Imaginary pinnacle				X	X		X		X			X	X		X	X								X		X		X	X	X		X	X

The design path matrix (Figure 5.17) represents the superposition of the two imaginary pinnacles for heat retention and dissipation, in order to determine the dominant features to be addressed in the integrated design concept. The dominant features (the highlighted nodes in orange) are the features that have the larger number of connections from the different imaginary pinnacles (different path colours), where the larger the number of connections the more dominant the feature becomes.

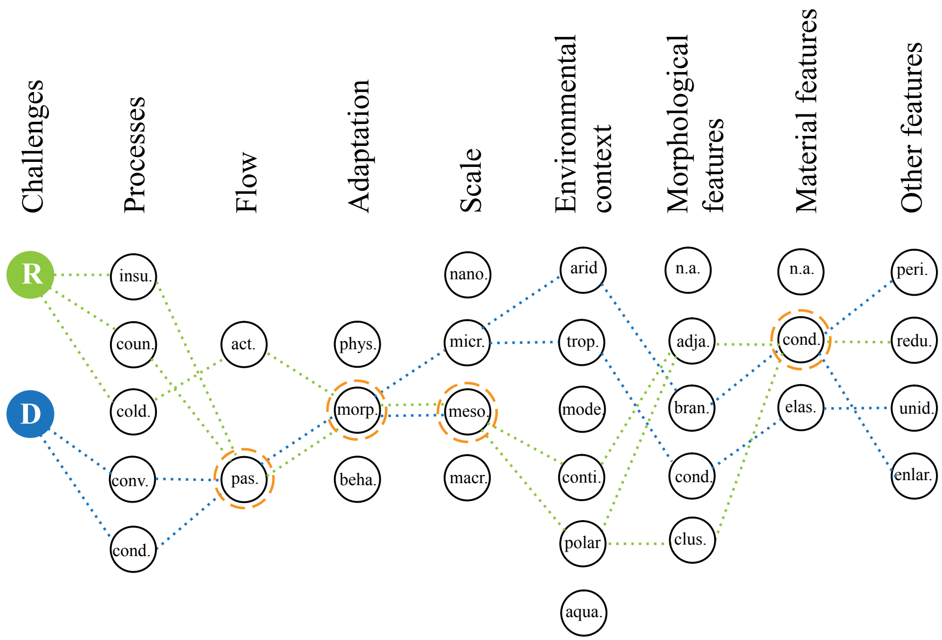

Figure 5.17

Design path matrix. Each vertical column represents a category and its various features. Green lines denote the path of heat retention, the blue lines denote the path of heat dissipation, and the orange nodes denote the dominant features which represent the design path.

The design path matrix for heat retention and dissipation indicates several properties from the various categories relevant for the design concept:

- Passive flow for both retention and dissipation
- The meso scale is a relevant scale for retention and dissipation
- Morphological adaptation influences both functions, which requires attention at the relevant morphological features for each imaginary pinnacle
- Hot environmental context for dissipation, and cool environmental context for retention
- Adjacent and cluster morphological features for retention
- Branching and conduits for dissipation
- Conductive material properties to be considered for both challenges
- Reduced surface area for retention
- Enhance conduction for dissipation
- Enlarged surface area and peripheral flow for dissipation

The derived dominant features provide guidelines for the design concept. Both imaginary pinnacles share morphological adaptation, but the specific morphological features are not shared. Thus, different configurations exist for each challenge of this particular case. Next step (5) illustrates the abstract graphical translation of the design path matrix.

5.4.5 **Preliminary design concept proposal** (step 5)

The proposed envelope is based on the principles extracted from the design path matrix (Figure 5.17). The envelope consists of two adjacent branching conduits for air circulation. One is for exhaust air and the other one for fresh air, where they flow in a counter-current for heat retention (Figure 5.18). A by-pass system for the fresh air supply is available when heat retention is not required (Figure 5.18).

The conduits that carry the fresh air to the inside run along the conduit that carries the exhaust air from inside to the peripheral chimney, as presented in Figure 5.19. By this special arrangement, the fresh air reaching the inside is warmed up gradually by gaining heat from the adjacent conduit of exhaust air. The conduit of the warm air branches before reaching the peripheral chimney, which increases surface area for heat exchange with the entering fresh air (Figure 5.19b). All these together, create an envelope with a temperature gradient that enables heat retention.

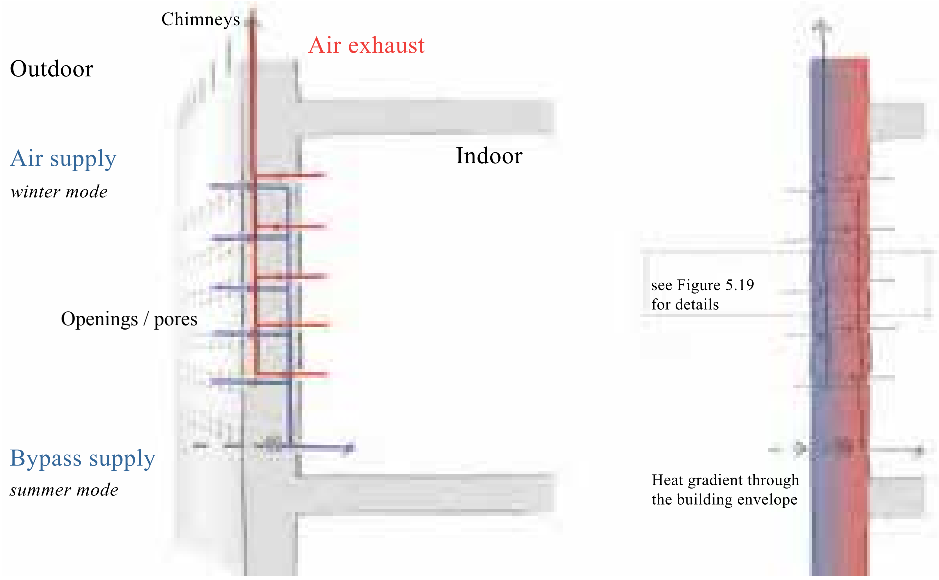

Figure 5.18

Abstract representation of the design concept. Colder air is supplied through openings/pores (winter mode), or through the bypass supply (summer mode). The configuration of the air supply and exhaust conduits create a counter-current flow during winter mode (left) resulting in temperate gradient in the cavity of the building envelope (right), thus reduce heat loss.

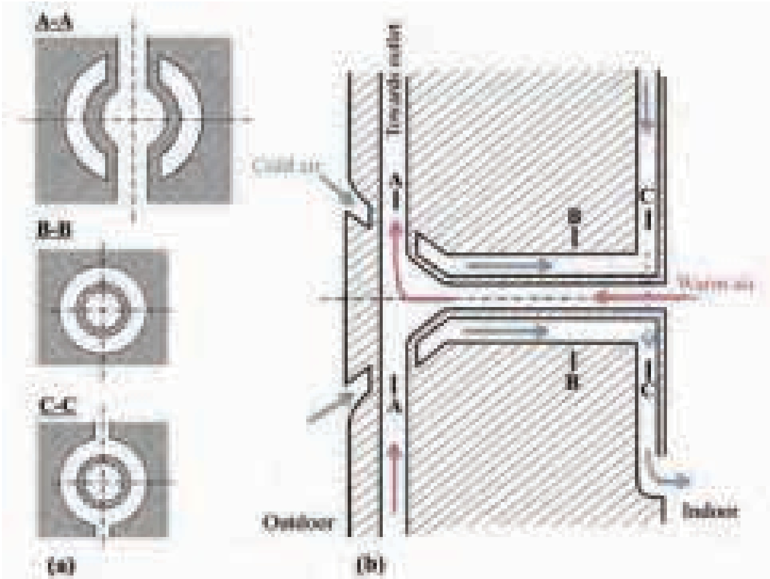

Figure 5.19

Cross sections showing the interlaced morphology that allow counter-current air flow of cold air and warm air to enhance heat exchange.

5.5 Conclusions

Thermoregulation mechanisms in nature were investigated (section 5.2) with the objective of implementation in building envelopes. Organisms succeed to maintain an adequate balance between heat gain and heat loss without creating air-tightness and water-tightness. Various strategies are found in nature for heat acquisition, retention, dissipation, and prevention, where they are accomplished by physiological, behavioural, and morphological means. The investigation of these strategies was summarized in an exploration model for thermoregulation (section 5.3), which provides a navigation tool to outline exemplary pinnacles corresponding to design challenges. The exploration model provides a focus on the links between four levels of interest: functions, processes, factors, and pinnacles.

An example for generating a system for heat retention in building envelopes was presented (section 5.4), where the pinnacle analysing matrix and the design path matrix were used in order to assist in distinguishing the proposed design characteristics, and narrowing the broad range of possibilities throughout the design process. The transformation of strategies available in nature into technical solutions for building envelopes is a complicated multidisciplinary process. It becomes even more complicated when integrating a number of strategies from different organisms to achieve improved solutions.

The proposed living envelope is a passive system, which is designed to retain heat while exchanging air based on the outcomes of the design tools (Table 5.2 and Figure 5.17). The envelope consists of conduits for air supply and conduits for air exhaust; they have a special morphological configuration that allows them to run in an adjacent and counter-current manner. In this way, the cooler air entering the medium gains heat from the indirect interaction with the leaving warm air, and thus minimizes overall heat loss from the interior. The heat exchange system is an integrated part of the envelope, which creates an envelope that functions as a medium between the outside and the inside for heat transfer.

References

Arens, E.A. & Zhang, H. [2006]. The Skin's Role in Human Thermoregulation and Comfort (Chapter 16). *Thermal and Moisture Transport in Fibrous Materials*, N. Pan & P. Gibson (Eds.), Cambridge: Woodhead Publishing LTD, pp. 560-602.

Air infiltration [2009], available online at: http://www.sustainable-buildings.org/wiki/index.php/Air_infiltration (retrieved July 2012).

Alistair Prentice [2011]. *Robin - Newry Canal*, available online at: http://www.flickr.com/photos/awprentice/6532361691/ (retrieved September 2012).

Bartholomew, G.A., Lasiewski, R.C., & Crawford, Jr., E.C. [1968]. Patterns of panting and gular flutter in cormorants, pelicans, owls and doves. *The Condor*, **70**, pp. 31–34.

Biology blog. *Vasoconstriction vs vasodilation*, available online at: http://gcsebiologyblog.blogspot.com/2008/08/comments-and-questions.html [retrieved July 2009].

Camargo, C.R., Visconti, M.A., & Castrucci, A.M.L. [1999]. Physiological color change in the Bullfrog, Rana Castesbeiana. *Journal of Experimental Zoology*, **283**, pp. 160-169.

Cameron Rognan [2010]. *Chuckwalla*, available online at: http://www.flickr.com/photos/cameronrognan/4613658476/in/photostream (retrieved July 2012).

Carey, F.G. & Teal, J.M. [1966], Heat conservation in tuna fish muscle. *Zoology*, **56**, pp. 1464-1469.

Cloudsley-Thompson, J. L. [1999]. Multiple factors in the evolution of animal coloration. *Naturwissenschaften*, **86**(3), pp. 123-132.

Coturnix [2006]. *A Blog Around The Clock,* available online at: http://scienceblogs.com/clock/ [retrieved July 2011].

Dawson, C., Vincent, J.F.V., Jeronimidis, G., Rice, G., and Forshaw, P., [1999]. Heat Transfer through Penguin Feathers, *J. theor. Biol*., **199**, 291-295.

Dove, C.J., Rijke, A.M., Wang, X., & Andrews, L.S. [2007]. Infrared analysis of contour feathers: the conservation of body heat radiation in birds. *Journal of Thermal Biology*, **32**, pp. 42-46.

Du, N., Fana, J., Wua, H., Chena, S., and Liub, Y., [2007]. An improved model of heat transfer through penguin feathers and down, *Journal of Theoretical Biology*, **248**, pp. 727-735.

Featherfolio [2008]. *Rock Hopper Penguin Feather*. Large shaft and lots of down keep the penguin warm, available online at: http://commons.wikimedia.org/wiki/File:Penguin_Rockhopper%2B.jpg (retrieved August 2012).

Gibson, A.C., Online lecture notes on "General Botany". Available online at: http://www.botgard.ucla.edu/html/botanytextbooks/generalbotany/index.html (retrieved September 2012)

Gilbert, C., Maho, Y.L., Perret, M., & Ancel, A. [2007]. Body temperature changes induced by huddling in breeding male emperor penguins. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology*, **292**(1), R176-R185.

Guyton, A.C. & Hall, J.E. [2000]. *Textbook of Medical Physiology*, Philadelphia: W.B. Saunders Company.

Hensel, H. [1982]. *Thermoreception and Temperature Regulation*. London: Academic Press.

Heyning, J.E. & Mead, J.G. [1997]. Thermoregulation in the Mouths of Feeding Gray Whales". *Science*, **278** (5340): pp. 1138–1140. doi:10.1126/science.278.5340.1138.

Hill, R.W., Wyse, G.A., & Andreson, M. [2008]. *Animal Physiology*, second edition, Massachusetts: Sinauer Associates, Inc., pp. 205-252.

Hohtola, E. [2002]. Facultative and obligatory thermogenesis in young birds: a cautionary note, Comparative Biochemistry and Physiology - Part A: Molecular & *Integrative Physiology*, **131**(4), pp. 733-739.

Jackson, T. [retrieved April 2012]. *The science of stripes*, available online at: http://www.safarikzn.com/africa-geographic-articles/page_africa_geographic_articles_science-of-stripes.html

Jones, J.C. & Oldroyd, B.P., [2006]. Nest Thermoregulation in Social Insects. *Advances in Insect Physiology*, **33**, pp. 153-191.

Kipervaser, D. [2003]. *Behavioral thermoregulation in terrestrial arthropods*, available online at: http://www.biologybrowser.org/node/1162349.

Korb, J. & Linsenmair, K. E., [1998]. The effects of temperature on the architecture and distribution of Macrotermes bellicosus (Isoptera, Macrotermitinae) mounds in different habitats of a West African Guinea savanna. *Insectes Sociaux*, **45**(1), pp. 51-65.

Korb, J. & Linsenmair, K. E., [1999]. The architecture of termite mounds: a result of a trade-off between thermoregulation and gas exchange?. *Behavioral Ecology*, **10**(3), pp. 312-316.

Korb, J. & Linsenmair, K. E., [2000]. Ventilation of termite mounds: new results require a new model. *Behavioral Ecology*, **11**(5), pp. 486-494.

Kvadsheim, P.H. & Folkow, L.P. [1997]. Blubber and flipper heat transfer in harp seals. *Acta Physiologica Scandinavica*, **161**(3), pp. 385-95.

Lemlich, R. [1955]. Effect of vibration on natural convective heat transfer. *Industrial and engineering chemistry*, **46**(6), pp. 1175-1180.

Lillywhite, H.B., & Stein, B.R. [1987]. Surface sculpturing and water retention of elephant skin. *Journal of Zoology*, **211**, pp. 727–734.

Luscher M., [1961]. Air conditioned termite nests. *Sci Am*, **238**, pp. 138–145.

Mackean, D.G., [2012]. *Birds: Feather Structure*. Available online at: http://www.biology-resources.com/drawing-bird-feather-structure.html (retrieved September 2012).

Meagher, E.M., McLellan, W.A., Westgate, A.J., Wells, R.S., Frierson, D., & Pabst, D.A.,

[2002]. The relationship between heat flow and vasculature in the dorsal fin of wild bottlenose dolphins Tursiops truncates. *The Journal of Experimental Biology*, **204**, pp. 3475-3486.

Mike Baird [2009]. *Great Egret (also known as the Great White Egret or Common Egret); parent on nest with chicks at Morro Bay Heron Rookery, USA*. Available online at: http://commons.wikimedia.org/wiki/File:Ardea_alba_-chicks_and_nest_-Morro_Bay_Heron_Rookery_-8.jpg (retrieved August 2012) .

Perez-Lombard, L., Ortiz, J., and Pout, C., [2008]. Areview on buildings energy consumption information. *Energy and Building*, **40**, pp. 394-398.

Sabinche [2005]. *Robin*, available online at: http://www.flickr.com/photos/sabinche/3395862/ (retrieved September 2012).

Schmidt-Nielsen, K. [1972]. *How animals work*, New York: Cambridge University Press.

Schmidt-Nielsen, K. [2007]. *Animal physiology: adaptation and environment*, New York: Cambridge University Press, pp. 217-297.

Scholander, P. F. & Schevill, W. E. [1955]. Counter-current vascular heat exchange in the fins of whales. *Journal of Applied Physics*, **8**, pp. 279-282.

Scholander, P.F. Walters, V., Hock, R., & Irving, L. [1950]. Body insulation of some arctic and tropical mammals and birds. *The Biological Bulletin*, **99**(2), pp. 225-236.

Stevenson, R. D. [1985]. The Relative Importance of Behavioral and Physiological Adjustments Controlling Body-Temperature in Terrestrial Ectotherms. *American Naturalist*, **126**, pp. 362-386.

Tattersall, G.J. & Milsom, W.K. [2003]. Transient peripheral warming accompanies the hypoxic metabolic response in the golden-mantled ground squirrel. *J. Exp. Biol.*, **206**, pp. 33-42.

Taylor, B.J. & Imbabi, M.S., [1998]. The application of dynamic insulation in buildings. *Renwable energy*, **15**, pp. 377-382.

Tracy, C. R. & Christian, K. A. [1986]. Ecological Relations among Space, Time, and Thermal Niche Axes. *Ecology*, **67**, pp. 609-615.

Tributsch, H. [1984]. *How Life Learned to Live: Adaptation in Nature*, Cambridge: The MIT Press.

Walsberg, G.E. [1983]. Coat color and solar heat gain in animals. *Bioscience*, **33**, pp. 88-91.

Walsberg, G.E. [1988a]. Consequences of skin color and fur properties for solar heat gain and ultraviolet irradiance in two mammals. *The Journal of Comparative Physiology*, **158**(2), pp. 213-221.

Walsberg, G.E. [1988b]. The significance of fur structure for solar heat gain in the rock squirrel, Spermophilus variegates. *The Journal of Experimental Biology*, **138**, pp. 243-257.

Walsberg, G.E., Campbell, G.S. & King, J.R. [1978]. Animal coat color and radiative heat gain: a re-evaluation. *The Journal of Comparative Physiology*, **126**, pp. 211-222.

Weathers WW. & Schoenbaechler, D.C., [1976]. Contribution of gular flutter to evaporative cooling in Japanese quail. *J Appl Physiol*, **40**, pp.521-524.

Zitterbart, D. P., Wienecke, B., Butler, J. P., & Fabry, B. [2011]. Coordinated Movements Prevent Jamming in an Emperor Penguin Huddle. *PLoS ONE*, **6**(6), pp. e20260.

Water

Chapter 6

6.1 Introduction

Water management and regulation in buildings have been facing real challenges with increasing environmental awareness during the last decades. Providing water and managing waste for buildings are major concerns for water regulation. Current concerns of shortage in water resources increase the demands to enhance water conservation strategies. In this respect, an efficient building should be able to gain, conserve, transport, and lose water. The gained water might be used, among others, for cooling purposes. Rainwater harvesting and the reuse of grey-water in buildings have been investigated thoroughly in the last years [e.g. Al-Jayyousi 2003, Herrmann & Schmida 1999, Fewkes 1999, Dixon *et al.* 1999]. The Council House 2 (CH2), a green building in Australia, represents one of the high performance buildings in water management. An important feature of the CH2 building is the five cooling towers, where air flows through and cools via water droplet evaporation, thus cooling the air temperature from 35°C to 21°C [Chapa 2007].

In the last few decades, various surfaces for water gain through condensation or concentration have been developed for the potential use as covering or application on existing surfaces, e.g. the super-hydrophobic sol-gel coating developed at the Sandia National Laboratories. The surfaces mainly mimic the nanoscale roughness necessary for the hydrophobic effect [Summers 2004] (which is similar to the surface of the desert beetle [Super-hydrophobia]). More hydrophobic and hydrophilic surfaces, for promoting droplet formation are under development to increase chances for droplet formation [e.g. Beetle-based water harvesting, Wong *et al.* 2011], and thus increase the efficiency of water collection. Another example for water collection is the water harvesting systems in South Africa; the system consist of a mesh screen upheld by poles, where water is collected from fog potentially to meet the needs of the local community [Olivier & Rautenbach 2002].

In the current chapter, some water regulation mechanisms found in nature are presented for the potential implementation in building envelopes, based on the living envelope methodology presented in chapter 3. A brief background on some water regulation strategies in nature, with a focus on water gain, conservation, transportation, and loss, is given in section 6.2. Exemplary organisms/systems, referred to as *pinnacles*, which are able to gain, transport, and distribute water in challenging environments (e.g. arid areas) the investigated functions, processes, factors and organisms/systems are summarized in an exploration model in section 6.3. An example of a design concept of fog-harvesting envelope in arid areas is presented in section 6.4. The envelope's main challenges are to attract, collect, transport, and distribute water optionally for cooling or humidifying the interior. To this end, corresponding pinnacles are obtained from the exploration model, and applied in a design path matrix, which results in the main features of the design concept. Finally, the concluding remarks are given in section 6.5.

6.2 Water regulation in nature

Water is essential for all forms of life. It covers more than 70% of the surface of Earth, and continuously moves through the hydrological cycle of evaporation (or transpiration), condensation, precipitation, and surface runoff reaching channels, and mostly transported via rivers to the sea. Water is essential to all living organisms as it acts as a solvent to provide a liquid environment for biochemical reactions, and it is an ideal lubricant to transport food; it is needed to maintain appropriate concentrations of body fluids, which may differ from those of the environment; and it has a high specific heat capacity[1] that allows maintenance of the internal energy, and enables cooling by evaporation [Thurow 2012].

This section provides a background on water regulation strategies found in nature. Special attention is given for organisms that live in deserts and have strategies for extreme adaptations, including abilities to obtain and conserve water, and prevent dehydration [Hill *et al.* 2008]. Water-balance physiologists find these organisms worth studying because of their extraordinary ability to live on as little water as possible. The various important functions and strategies for water regulation are too many to be listed and elaborated on in the scope of this chapter. Thus, the focus is put on specific strategies of water gain, transportation, conservation, and loss in arid environments.

6.2.1 Water gain

Drinking is one of the obvious forms of water gain. However, this study explores other water gain strategies, and looks at regions with limited water resources. Surface condensation and transport to the mouth and uptake via body surface (diffusion) are examples of methods for gaining water in environments where water resources are limited.

6.2.1.1 Condensation

Fog represents an alternative source of water for organisms in deserts. The cold coastal currents can bring rainfall over the desert, and generate fog that can reach as much as 100 km inland from the coast in some regions [Ward *et al.* 1983]. For example, these fog events (at 10-12°C) are estimated to occur around 30 days per year in the Namib Desert [Lancaster *et al.* 1984]. Condensation is highest near dawn, when the relative humidity is highest [Louw 1972]. This affects animal eating habits (gaining water from condensed water on plants), preferring eating at dawn rather than in the evening [Hill *et al.* 2008]. Various strategies are employed by organisms to gain water through condensation in deserts. Some organisms, such as Tenebrionid beetles, dig trenches in the sand to catch water, which are constructed perpendicular to fog winds [Seely & Hamilton 1976], while others, e.g. Onymacris unguicularis (a fog-basking Tenebrionid beetle), use their skin surface for condensation for water collection [Hamilton & Seely 1976], see Figure 6.1. In plants, the small size of leaves has been observed as an important factor affecting water harvesting [Martorell & Ezcurra 2007], since it is hard for the wind to blow condensed water from narrow and small leaves due to their thin boundary layer [Nobel 1988], e.g. hairy leaves in succulents (Figure 6.1). Cacti have lots of spines (an adapted variation for leaves for less reducing water loss) that increase condensation, and channel the collected water down to their roots. The surface morphology and property have a major effect on condensation collection. Additionally, alternating hydrophilic and hydrophobic regions have been shown in beetles to improve water capture from fog [Parker & Lawrence 2001].

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1 "*This means that a relatively large amount of energy must be applied to raise the temperature of one gram of water one degree centigrade; this amount of energy is defined as a calorie. This property gives water a great deal of temperature stability and facilitates maintenance of a steady temperature within an organism.*" [Thurow 2012].

Figure 6.1

Water vapour condensing on: (a) the ends of cactus spines – courtesy of George Shuklin [2007], (b) the trench of Flying saucer beetle – courtesy of Brian Chiu [2007], and (c) the body of a beetle – provided by © Solvin Zankl.

6.2.1.2 Diffusion

Some terrestrial organisms, including many amphibians, are able to absorb water vapour directly from the air via their skin. As an example, green tree frogs produce condensation on their skin by hopping from a chilly to a warm environment, and soak the dew generated on their body through theirs porous skin [Strain 2011]. The ventral side of the skin of the green tree frog has ridges and grooves (Figure 6.2), and the capillaries which are invaginated in the ridges allow absorption of water [Goniakowska-Witalinska & Kubiczek 1998]. In this case the skin functions as water harvesting system; collecting water from vapour and passively diffusing through the skin.

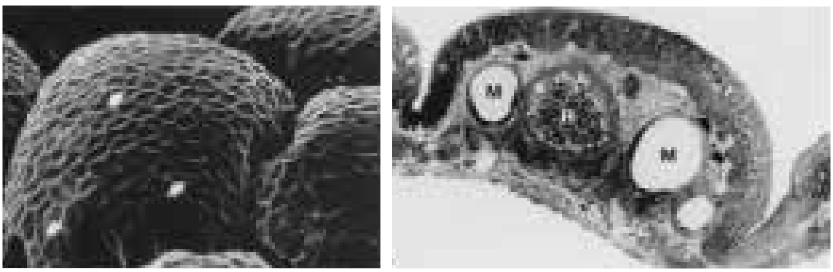

Figure 6.2

Left: the surface of the ventral skin consists of ridges and deep narrow grooves. Right: capillaries of about 8-9 mm in diameter are invaginated into the epithelium of ventral skin together with the connective tissue surrounding them. Reproduced from [Goniakowska-Witalinska & Kubiczek 1998], used with permission from Elsevier.

6.2.2 Water transportation

Nature consists of a large amount of water, and has the ability to move water from one region to another. However, the movement is not necessarily random and some physical laws apply on water transportation. Water can be transported at large range of scales; it can be transported, among others, due to gravity (e.g., rivers) or via capillary action (e.g., xylem in plants).

6.2.2.1 Gravity

Water moves naturally by the forces of gravity. Some organisms have adapted special morphologies to take advantage of gravity and direct water to their roots; hence increase water gain, especially in arid regions, e.g. agave. Agave is a succulent with a large rosette of thick fleshy leaves, where leaves end in a sharp point and have spiny edges, as shown in Figure 6.3, left. The concave shape of the leaves directs the rainfall or condensed water toward the roots, as these leaves spring from the roots. Ribs or grooves are another morphological adaptation for water transportation, e.g. barrel cactus. Besides the importance of these ribs in allowing the cactus to shrink and swell, they provide channels for the collected water to reach the roots (Figure 6.3 right).

Figure 6.3

Left: Agave's leaves funnel water to the centre of the plant root – courtesy of Stan Shebs [2006]. Right: barrel cactus – courtesy of Kaldari [2009].

6.2.2.2 Capillary action

Capillary action is the tendency of a liquid (e.g., water) to move counter to gravity in a narrow tube, or in porous material such as paper. It occurs due to the intermolecular attraction within the liquid and the solid surrounding surfaces [Capillary Action 2011]. The adhesion of liquid molecules pulls some water along the wall of a tube, see Figure 6.4, left. Capillary action is influenced by: (1) the diameter of the tube, (2) density of liquid and gas (which are function of temperature), (3) the acceleration of gravity, (4) the contact angle (liquid with tube wall), and (5) the surface tension of the liquid (which is caused by cohesion within the liquid). The narrower the capillary tube the higher the liquid raises. In a smaller capillary tube, the liquid mass (per unit cross-sectional area) is lower and the adhesion of liquid can hold a longer liquid column [Robinson 2009], see Figure 6.4, right.

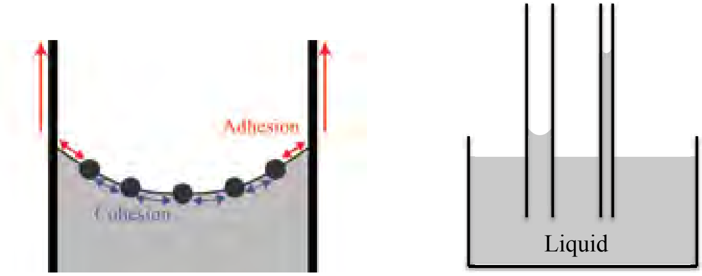

Figure 6.4

Left: cohesion and adhesion in a tube. Cohesion tends to minimize the area of free surface, and adhesion tends to pull the surface to the boundaries. Right: Illustration of capillary rise.

For example, capillary action is observed to transport water in plants. However, since adhesion forces can lift water only to a certain degree, fluid transportation from the roots of some plants can not occur only by capillary action. Trees transport water to the other parts by osmosis (solute concentration difference), where the plant looses water from the leaves and result in lifting water from the roots (the capillaries of the plant) to replace it [Capillary Action 2011], known as vapour pressure deficit. Furthermore, some desert lizards, e.g. Thorny Devil, have a special integument that is able to transport water, even from ground, and channel it to their mouth via capillary action [Bently & Blumer 1962, Sherbrooke *et al.* 2007]. Some researchers argue that the morphology and layout of these capillary tubes influence the efficiency of capillary action, e.g. fractals. Figure 6.5 shows some examples for capillary action for two dimensional (leaf veins) and for three dimensional transportation (tree roots).

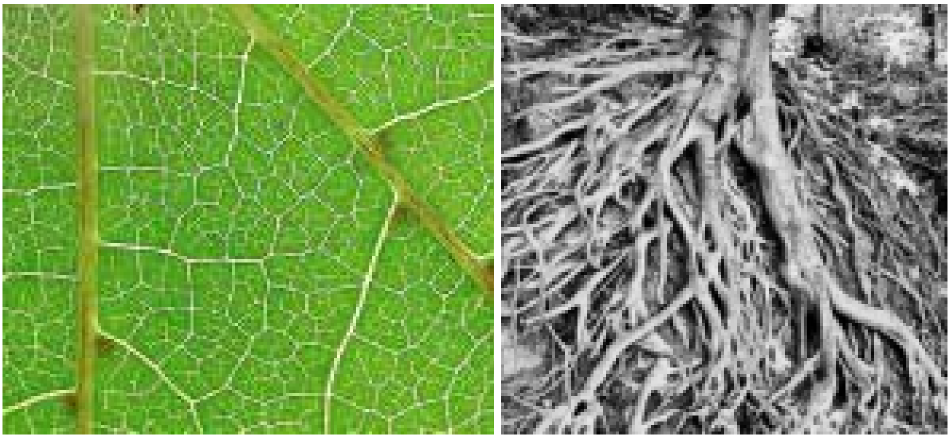

Figure 6.5

Patterns to transport liquids. Left: leaf veins – courtesy of Jim Conrad [2008]. Right: tree roots – courtesy of Lynne Jenkins [2009].

6.2.3 Water loss

Organisms lose water by three means [Schmidt-Nielsen 2007]: cutaneous water loss (through skin), excretory water loss (through urine and feces), and respiratory water loss (during gas exchange). Water loss through skin (sweating) is one of the mechanisms for thermoregulation (latent heat transfer). The interplay between thermoregulation and water loss may create a conflict: organisms want to lose heat and at the same time prevent dehydration. The higher the temperature gets the higher the evaporation rate becomes, and the drier the atmosphere gets the faster the evaporation rate becomes. Several internal and external physical factors influence the rate of evaporation in organisms, for example [Schmidt-Nielsen 2007]:

- **Vapour pressure difference**. This is expressed as the difference between the vapour pressure over a free water surface at a specific temperature and the water vapour pressure in the air.
- **Flow rate of air**. Airflow is a major factor, as it renews the air layer near the outer surface of an organism resulting in enhanced evaporation.
- **Temperature**. Warmer surfaces increase the evaporation rate. Water evaporation increases with temperature, since the air particles have a higher average kinetic energy, which is able to transport larger amounts of vapour.
- **Surface area and orientation**. The larger the surface area is the faster the evaporation occurs, as there is more surface area for particles to contact air and evaporate. The orientation and the curvature of the evaporating surface influence the rate of evaporation from the surface. This is due to the difference between convection currents produced on vertical and horizontal surfaces as a result of cooling.

6.2.4 Water conservation

Water conservation is important where water is limited. Reducing evaporation rates and reducing radiation exposure are common means in some organisms for water conservation.

6.2.4.1 Reduction of evaporation rate

Evaporation rate can be decreased by decreasing the temperature. For example, nasal passages cool exhaled air and condense water along the passageways in many desert lizards and rodents [Schmidt-Nielsen *et al.*1970]. "*The exchange of heat (and water) between respiratory air and the nasal mucosa depends upon several physical factors: (1) the surface area available for heat exchange, (2) the distance from the center of the air stream to the nearest surface, (3) the velocity of the air flow, and (4) the blood flow within the nasal tissues.*" [Murrish & Schmidt-Nielsen 1970]. As a result, "*heat exchange is facilitated by a large surface area, low air velocity, and a short distance to the wall.*" [Murrish & Schmidt-Nielsen 1970].

The existence of scales and waxy coating prevent evaporation through the skin [Jaeger 1957], e.g. reptiles and cacti (respectively). Additionally, some plants (CAM plants) can control the opening of stomata for lower transpiration rates [Björn & Govindjee 2008]: the stomata close during the day and open at night when transpiration rates are low (no solar radiation and low temperatures).

6.2.4.2 Reduction of radiation exposure

Reducing solar radiation exposure is a means, among some organisms, to prevent high heat loads, which result in high evaporation rates. Shiny reflective surfaces are found among organisms in deserts to reduce heat loads [Schmindt-Nielsen *et al.* 1971], e.g., skink. Fur and hair reflect a large amount of radiation before reaching to the skin surface where evaporation might occur, e.g. leaf hairs on many desert plants [Jaeger 1957]. Self-shading forms reduce radiation yet retain a large volume for water storage. The reduction of solar radiation exposure can be achieved through dynamic means (nastic motion[2]), for example:

Folding

Many plants have the property of folding to prevent transpiration water loss [Bar-Cohen 2006]. The folding or rolling is either downwards or upwards, and can also be along the main axis. The position of the *bulliform cells*[3] (top or bottom) determines the folding direction, where it creates differentiated top-bottom elasticity [Moulia 1994]. When they are dehydrated and contracted, the surface will get smaller which results in folding (see Figure 6.6). Note that this process is reversible.

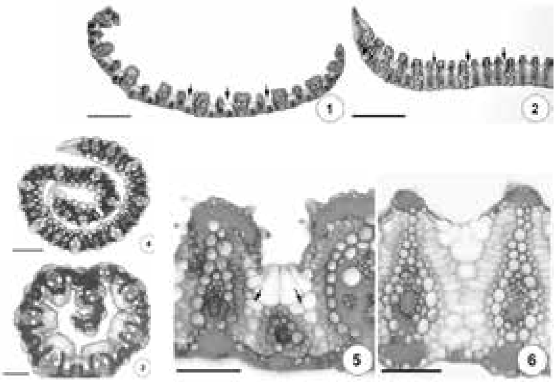

Figure 6.6

Left: dehydration causing leaf curling – courtesy of Henderson [2012]. Right: "*Expanded leaf blade (1) and (2) showing bulliform cells (arrows) on the adaxial surface, in groups in the intercostal zone. 3-4. Leaf blades rolled under dissection. 5. Conspicuous bulliform cells associated with columns of colourless cells (arrows) in the mesophyll. 6. Smaller bulliform cells connected to the chlorenchyma. Scale bars = 250µm (1), 208µm (2), 400µm (3, 4), 66µm (5), 40µm (6), 114µm (7).*" Reproduced from Alvarez et al. [2008], courtesy of Brazilian Archives of Biology and Technology.

Reorientation

Some plants prevent orientations perpendicular to solar radiation in order to reduce heat loads. As the cells of these plants dehydrate and shrink the stem bends, which is related, besides to physiology, to cell architecture and configuration. For example, the centralization of vascular bundles in the leaf stalk allows the leaf to bend. A certain chemical reaction results in a simple and reversible buckling, which causes the leaf to drop vertically [Fitting *et al.* 1950]. When a group of cells in plants increase their water

2 "*In the plant kingdom, plants are capable of localized movement due to a biological process called nastic motion in specialized motor cells. This occurs when biochemical reactions cause water to flow into or out of the motor cells, causing cellular volume change and overall tissue deformation. When the plant tissue undergoes non-uniform elongation from increased osmotic pressure or shrinkage from a decrease in pressure, the tissue will have bending deflection.*" [Giurgiutiu *et al.* 2005].

3 Bulliform cells are: "*enlarged epidermal cells that facilitate leaf rolling in response to water stress.*" [Roberts 2012].

content (swell due to increase in volume), and cells parallel to them shrink or remain with no change, the volumetric changes result in bending [Giurgiutiu *et al.* 2005]. If this happens at a large scale in the body plant it will cause a deformation of the stem or leaf, or allow a flower to open and close [Nastic Structures 2011]. As a result, such plants prevent orientations perpendicular to solar radiation, thus reduce heat loads.

Volume flexibility

This property is related to the entire body of plants shrinking or extending. Paturi [1976] reports on the submergence of the mescal cactus below the desert ground at the cold season by shrinking and reducing shoot length as an extreme case for adaptation in deserts (see Figure 6.7). The mescal cactus shrinks from top down in the ground at the beginning of the cold season (to keep warm and shelter from strong winds), and by the first rainfall the shoot hydrates (swells) and re-emerges above ground into light and open air [Paturi 1976]. Other desert plants have the property of shrinking their shoot while having the same surface area; in this case the surface is transformed from a concave to a convex shape, see Figure 6.8 [Bar-Cohen 2006]. This unique change is possible due to the ribbed columns, which provides an effective self-shading situation for the plants at extensive exposure to sun-radiation [Paturi 1976].

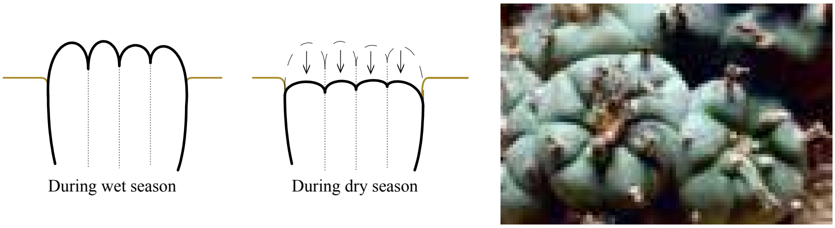

Figure 6.7

Left: Mescal cactus shrinking in the dry season underground. Right: upper part of the Mescal cactus – photo by Stolz [2008], courtesy of U.S. Fish and Wildlife Service.

Figure 6.8

Left: hydrated cacti – Courtesy of Topinambour [2004]. Middle: dehydrated cacti – Courtesy of Sue Winkler [2011]. Right: (1.) The corresponding cross-section of the saturated cacti (convex). (2.) The corresponding cross-section of the dehydrated cacti (concave).

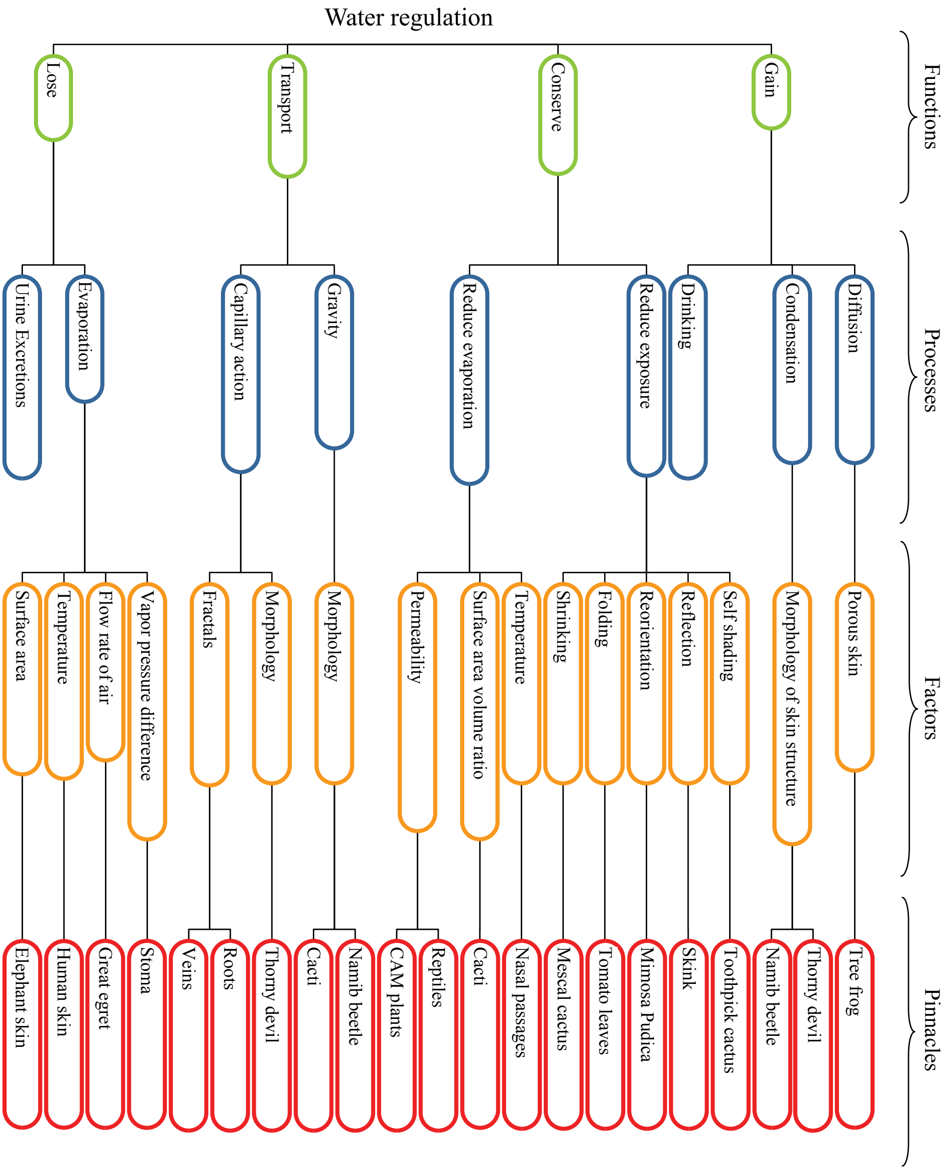

Figure 6.9 ....

Exploration model for water regulation.

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6.3 Exploration model for water regulation

The exploration model flowchart is based on four hierarchical levels. On the first level the functional aspects were identified: water gain, conservation, transportation, and loss (see Figure 6.9). Several processes were determined for each function, and sometimes sub-processes were identified. Numerous factors were determined to influence the processes of the functions, where material properties and morphological features greatly shape these factors. From the literature review, several representative pinnacles have arisen to demonstrate such processes, which are summarized in the last level of pinnacles.

Besides the hierarchical representation of the exploration model it provides a specific classification at some levels of the functions. The pinnacles for water gain and conservation are relevant in arid climates, whereas the pinnacles for transportation and loss are relevant in variable climates. This indicates that for water gain challenges it is advised to investigate pinnacles inhabiting arid regions, and for water loss challenges it is advised to give a special attention to the environmental aspects presented in the factors level (e.g. flow rate of air).

The various entities of the exploration model were explored and defined in the previous section (6.2). The content of the presented model is a representative state for the current exploration, where it can be extended and new entities at the various levels may be added in future elaborations. The systematic representation of entities and their relationships support the access to relevant information, which is further discussed in the following section by an example.

6.4 Example: water harvesting system

The increasing awareness of limited water resources, especially in arid regions, requires innovative designs that utilize the environmental potentials for water gain. Some arid regions have numerous fog events that occur at dawn and last for 3 hours, which provide a major water source for some local organisms. There have been several attempts to do a similar thing with water collection – provide water supply from fog for occupants. However, these solutions are not an integrated part of the building, and do not utilize the potential of the large surface area of the building envelope. Building envelopes are exposed to dynamic environmental changes, which has a great potential to function at water collectors with a proper design. The collected, besides being a water supply, might be used as a cooling source via humidification.

6.4.1 Definition of the design challenges (step 1)

The challenge defined for the current design is to collect water in arid regions, store the collected water, and optionally to contribute in humidifying and cooling the interior space via evaporation.

6.4.2 Identification of exemplary pinnacles (step 2)

"Collect water in arid regions" is related to alternative water gain sources. As indicated previously, for water gain challenges it is advised to investigate pinnacles inhabiting arid regions. Thus, water gain is the relevant function to be selected from the exploration model (Figure 6.9). The corresponding process is condensation, which might utilize the fog events occurring in the surrounding environments. Furthermore, the pinnacles corresponding to the selected process (condensation) are relevant for arid regions, which were advised earlier to be considered.

"Store the collected water" is relevant for transportation and conservation functions from the exploration model; water has to be transported from the collecting points to the storing points. The corresponding processes for transportation are: (1) gravity, which is influenced by morphology, and (2) capillary action, which is influenced by material properties and morphology. Both processes require no energy. The corresponding process to be selected for conservation is to reduce evaporation, as the other process to reduce exposure might have a conflict with the other process of condensation that requires special morphology of skin structure (e.g. in order to enlarge surface area).

"Contribute in humidifying… via evaporation" is related to the function loss from the exploration model. The corresponding process is evaporation, where several factors might affect it. Changes in vapour pressure and temperature influence air humidity of the occupied spaces, thus the corresponding pinnacles stoma and human skin are selected.

Figure 6.10 presents the chosen paths from water regulation exploration model, and the representative pinnacles are analyzed and summarized in the next section.

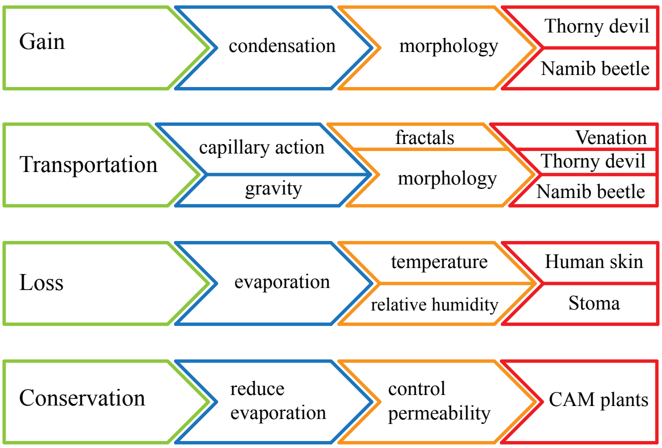


Figure 6.10

The extracted exploration paths.

6.4.3 Analyses of the selected pinnacles (step 3)

This step investigates adaptation mechanisms of the pinnacles selected for their water regulation mechanisms. The following pinnacles are explored based on relevant literature from biology: (1) Thorny Devil and Namib beetle for water gain and transportation, (2) Venation for transportation, (3) human skin and stoma for loss, and (3) CAM plants for conservation. The summary of the analysis is presented in section 6.4.3.1.

Pinnacle 6.1 **Thorny Devil** – water gain by moisture-harvesting & transportation

The Thorny Devil is a lizard living in the arid regions of Australia. The Thorny Devil is able to collect water from puddles via capillary forces generated in limb scale hinge-joint channels, and to transport it over the integumental surfaces leading to the rear angle of the jaws for drinking, as presented in Figure 6.11, left [Sherbrooke *et al.* 2007]. Additionally, it is able to collect water via condensation forming on its integument, suck dew off rocks, and from leaves [Thorny Devil 2011]. This ability is called rain or moisture-harvesting [Sherbrooke 1990]. Two factors influence rain-harvesting: (1) special behaviour combined with a specific body posture, and (2) certain morphology of the integument.

The integument (consists of the skin and the scales, from latin integere: to cover) has a major role in transporting the water to the mouth. The micro-channels of the scale-hinges [Sherbrooke *et al.* 2007] and the honeycomb-shaped micro-structure [Peterson 1984] are the main features of this special integument. The micro-channels form a semi-tubular capillary system over the body (Figure 6.12), which transports the water to the mouth [Sherbrooke 2004], and the micro morphology of the integument creates a super hydrophilic surface for an efficient water transport [Comanns *et al.* 2011].

The scales of the integument differ in size and shape, depending on body location. Unlike the inner side, the scales' outer side consists of micro ornamentations (Figure 6.13) [Peterson 1984]. This special morphology of the integument results in a contact angle less than 10°, which makes this surface super hydrophilic [Comanns *et al.* 2011]. Increasing the roughness of a hydrophilic surface will decrease its contact angle [Quere 2008].

The interscalar capillary network transports the collected water towards the mouth. The mouth acts as a water sink (due to its opening and closing movements) and results in sucking the water through the capillary system from the whole body surface [Comanns *et al.* 2011]. Bently & Blumer [1962] and Sherbrooke *et al.* [2007], argue that this mechanism is due to the capillary forces generated on the narrow grooves covering the lizards' skin.

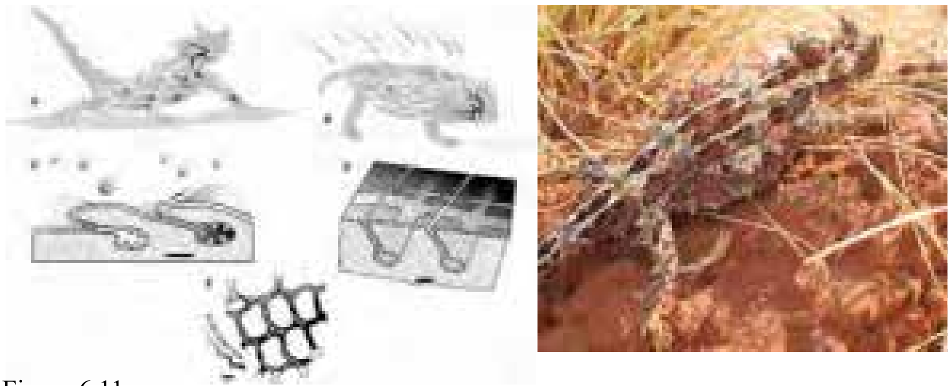


Figure 6.11

Left: Schematic representations of two rain-harvesting lizards, Moloch horridus (Agamidae) and Phrynosoma cornutum (Iguanidae). Reproduced from Sherbrooke *et al.* [2007], used with permission from Springer. Right: Thorny Devil in the Australian outback.

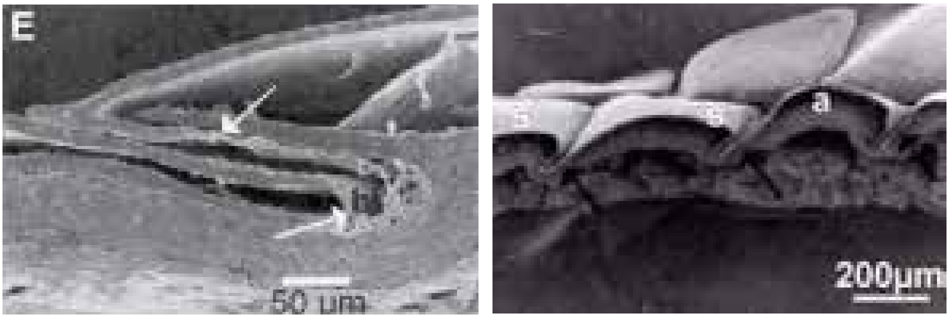


Figure 6.12

Left: “SEM cross-section of scale hinge extending between two scales into a hinge joint which is compressed by a shifted relationship between the two scales. The hinge joint exhibits surface bulging, increasing its internal surface area”. Right: “SEM cross-section of ventral body wall and scales (indicated by s)”. Reproduced from Sherbrooke *et al.* [2007], used with permission from Springer.

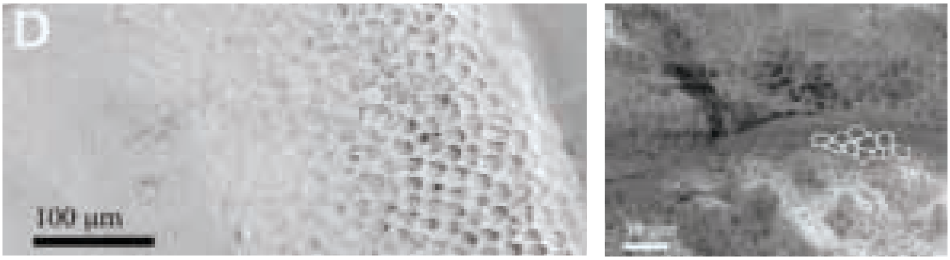


Figure 6.13

Left: “towards the edge (right) of the scale a honeycomb like structure is visible, while the centre of the scale is hardly structured”. Right: “Moloch Horridus shows the honeycomb like micro ornamentation virtually all over the scales”. Reproduced from Comanns *et al.* [2011], courtesy of *Beilstein-Institut*.

Pinnacle 6.2 **Namib Desert Beetle** – water harvesting and transporting

The Namib Desert beetle inhabits one of the harsh environments on earth, which experiences high winds, extreme temperatures during the day, and dense fog at dawn [Crawford 1981]. Despite the lack of water resources some organisms can still survive such habitat. It has been reported that the Namib Desert beetle is able to collect water from fog by a fog-basking behaviour (Figure 6.14 left). The fog-basking behaviour is a physical posture, where the head is pointing down facing the wind with the elytra (the hardened forewing, also called wing case). By this posture, the water is collected on the elytra by condensation, and directed down to the beetle’s mouth [Hamilton & Seely 1976].

A combination of hydrophilic and hydrophobic regions by means of elevated bumps (Figure 6.14, middle and Figure 6.14, right) the beetle is able to attract water droplets from the fog and channel these droplets to the mouth. The bumps strongly attract water, while the waxy areas repel it. As the beetle is fog-basking, water droplet stick on the hydrophilic peaks and grow until they reach a specific size and roll down through the hydrophobic grooves of the elytra to the mouth [Parker & Lawrence 2001].

Nonetheless, Nørgaard & Dacke [2010] argue that the fog-basking behaviour, by standing at the top of the sand dune and taking the fog-basking posture (an angle of approximately 23°, Figure 6.14, left), is the important factor allowing the beetle to use the fog as an alternative source of water in the Namib Desert.

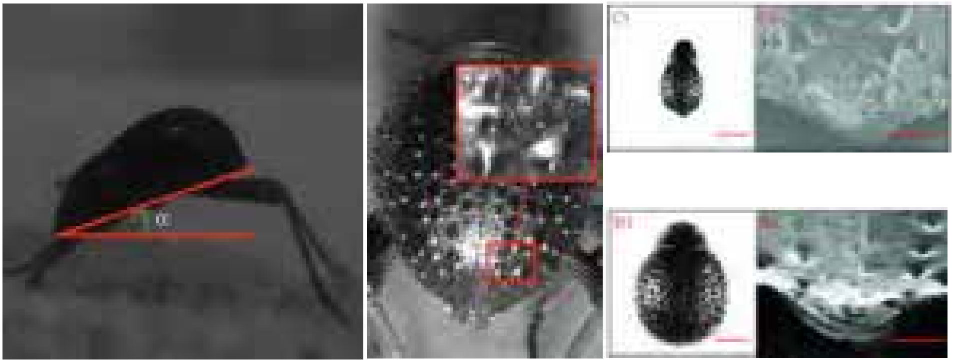


Figure 6.14

Left: "Fog basking posture of Onymacris unguicularis. This posture allows fog water collected on the beetle's dorsal surface to trickle down to its mouth". Middle: "Hydrophobic dorsal surface of Physasterna cribripes, the magnification shows the shining hydrophobic peaks of the bumps on the elytra". Right: "Extended Depth Focus images of examples of the experimental animals obtained with a dissection microscope. Scale bar = 5 mm. (C2-D2) SEM images of the apex of the elytra. Scale bar = 1 mm." Reproduced from Nørgaard & Dacke [2010], courtesy of *Frontiers in Zoology*.

Pinnacle 6.3 **Venation networks in leaves** – water transportation and distribution

Venation is the distribution or arrangement of a system of veins. The pattern of venation networks in leaves responds to functions such as carbon intake and water use [Blonder *et al.* 2011]. Leaf venation patterns which include a dense set of loops were observed to be an optimal transportation network even at events of damage [Katifori *et al.* 2010]. The complex hierarchical network of nested loops in the leaf, instead of the linear, allow flow to be routed around the damaged veins [Katifori *et al.* 2010], as presented in Figure 6.15. Networks with hexagonal traits achieve high potential loops for a specific vein density and distance [Blonder *et al.* 2011], where these hexagons were observed as well in the cells of soap films that are characterized by their minimal surfaces [Weaire & Rivier 1984].

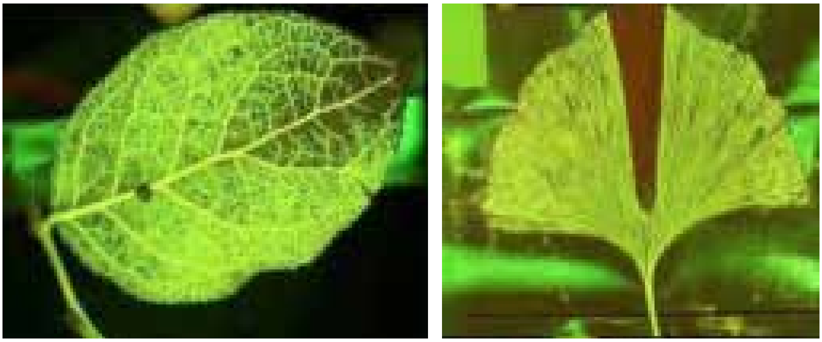


Figure 6.15

Distribution network of interconnected loops like the one in the lemon leaf (left) is better able to handle damage (green hole) and fluctuating loads than the more straightforward - and evolutionarily more ancient - distribution system in the gingko (right). Reproduced from Rockefeller University [2010], used with permission from Eleni Katifori, images courtesy of Rockefeller University.

Pinnacle 6.4 **Human skin** – water evaporation

The skin provides a medium between the organism and the surrounding environment, which controls heat and moisture transfer in response to thermoregulatory demands of the body. The skin thickness is about 2 mm, though it may vary locally. It contains a complex vascular system and sweat glands, and includes two main layers: the epidermis and the dermis. The epidermis is the outermost layer of the skin, and the primary barrier to water diffusion [Forslind & Lindberg 2004]. The dermis is much thicker than the epidermis and contains vascular systems, sweat glands, and thermoregulatory nerves [Rushmer *et al.* 1966]. When sensible heat transfer becomes insufficient for heat removal, then moisture evaporation (latent heat transfer) becomes an efficient heat removal process. Eccrine sweat glands through their openings on the skin surface provide moisture on the skin. Increasing the secreted sweat to the skin surface is achieved both by increasing the number of contributing sweat glands and by increasing the amount of output of each active glands. An increase in the output of each gland was observed as the primary result of overheating, rather than increasing the number of participating sweat glands [Randall 1946, 1947].

Pinnacle 6.5 **Stoma**

Little pores called Stomata (singular of stoma) open or close to control gas exchange and prevent too much water loss in plants. They are positioned generally more on the lower epidermis, however, on floating leaves they could be only on the upper epidermis. The stoma consists of two highly specialized cells (guard cells) with tight radial micro-fibril bundles at the ends and loose in the middle [Aylor *et al.* 1973], see Figure 6.16. The different properties of the guard cell's walls ensure an uneven expansion when inflated [Atwell *et al.* 1999]. An increase in osmotic pressure in the guard cells results in inflation and as a result creates an opening. Reduction in the osmotic pressure reduces the volume of the guard cells and results in closing to prevent too much water loss [Franks & Farquhar 2007].

Many species have stomata partly covered by epidermal cells, which creates a microclimate to protect the stoma from winds and atmospheric vapour pressure deficiency, and to mitigate transpiration on hot and dry days [Atwell *et al.* 1999]. Different factors influence the opening and closing of the stomata, which include: light intensity, humidity, and carbon dioxide concentration [Franks & Farquhar 2007]. For example, in desert plants (called CAM plants) the stomata open at night to prevent too much water loss during the day [Björn & Govindjee 2008].

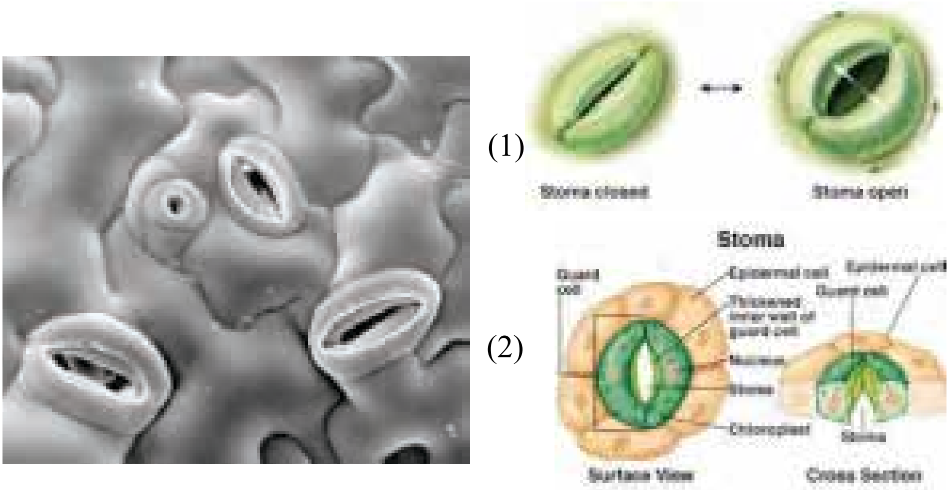


Figure 6.16

Left: Scanning electron microscope image of *Lycopersicon esculentum* (Tomato) lower leaf surface, showing stoma – by Louisa Howard, courtesy of E.M. Lab, Dartmouth College. Right: (1) stoma at closed and open states, reproduced from Brooker et al. [2008], used with permission from © McGraw-Hill Companies. (2) Anatomy of stoma, reproduced from McGraw-Hill [2000], used with permission from © McGraw-Hill Companies.

Pinnacle 6.6 **CAM plants** – water conservation

CAM (Crassulacean Acid Metabolism) plants are organisms that pose physiological adaptation to extremely hot and dry environments, e.g. cacti, orchids, pineapple, and some ferns [Fitter & Hay 2002]. CAM plants extend photosynthesis process over a 24 hour period, where stomata open at night (CO2 uptake occurs) and close during some of the day [Björn & Govindjee 2008]. At night, temperatures are low and relative humidity is high, thus ensure minimised water loss and lead to water conservation [Govindjee *et al.* 2005].

6.4.3.1 Pinnacle analysing

The summary of the analysis of the six pinnacles extracted from the exploration model is presented in Table 6.1., which provides a functional guideline for the design process. Thorny Devil and Namib Desert beetle represent the mechanisms for water gain and transportation, venation represent mechanism for water transport alone, the human skin and the stoma represent the mechanisms for water loss, and the CAM plants represent mechanisms for water conservation.

Table 6.1 Summary of pinnacles analyses

Pinnacle's strategy	Mechanism	Main principle	Main feature
Thorny Devil Collects and transports water over the integument surface leading to the mouth via capillary forces	Capillary forces generated in the integument due to the micro-channels of the scale hinges and the honeycomb-shaped structure	Capillary action for water transport	Moisture-harvesting
Namib desert beetle Collects water from fog by condensation on the elytra	A special arrangement of hydrophilic and hydrophobic areas on the elytra results in attracting water droplets and transporting it to the mouth	Bumpy surface for water attraction	Fog-basking behaviour
Venation networks Transport and distribute liquids in a network of conduits in order to reach the required cells of the organism via diffusion and capillary forces	A dense set of loops of veins optimize water transportation and distribution	Complex hierarchical network of nested loops	Water transportation and distribution
Human skin Contains a complex vascular system and sweat glands for evaporative cooling	Secreting sweat to the skin surface removes heat by evaporation	Latent heat transfer for cooling	Sweating
Stoma Open and close for gas exchange in response to osmotic pressure in the guard cells	The thick elastic inner walls and thin elastic outer walls of the guard cells, ensure an uneven expansion when inflated, thus result in the opening.	varied elasticity for uneven expansion	Elasticity & expansion
CAM plants Protects photosynthesis process from both water and CO2 stress by extending the process over day and night (24 hours).	Opening stomata at night to prevent water loss, when ambient temperatures, and water vapour concentration difference between the tissues and ambient air are low	Responsive stomata permeability	Water conservation

6.4.4 **Design path matrix** (step 4)

In the current example, water gain, transportation, loss, and conservation are the addressed challenges (see Table 6.2). For each challenge nine categories are presented, e.g., processes, flow, adaptation, scale, etc. The cross signs denote the corresponding features of each pinnacle in each category.

Summary of pinnacles analysis

Table 6.2

		Processes						Flow		Adaptation			Scale				Environmental context						Morphological features				Structural features			Material features				Other features				
Challenges	**Pinnacles**	Condensation	Capillary action	Diffusion	Evaporation	Control permeability	Gravity	Active	Passive	Physiological	Morphological	Behavioural	Nano	Micro	Meso	Macro	Arid	Tropical	Moderate	Continental	Polar	Aquatic	Thorns	Bumpy	Hexagonal	Fractal	Tubes	Grooves	Channels	Hydrophobic	Hydrophilic	Elastic	Waxy	Vibration	Porous	Overlaps	Folding	Asymmetric expansion
Gain																																						
	Thorny Devil	X							X		X			X			X						X	X					X		X							
	Namib beetle	X							X		X	X		X			X							X					X		X							
	Imaginary Pinnacle	X							X		X			X			X							X					X		X							
Transportation																																						
	Thorny Devil		X						X		X			X			X								X				X	X						X	X	
	Namib beetle						X	X				X		X			X											X		X								
	Venation		X						X		X			X			X	X	X	X						X	X											
	Imaginary Pinnacle		X						X		X			X			X								X	X	X	X	X	X						X	X	
Loss																																						
	Human skin				X				X	X				X			X	X	X	X															X			
	Stoma			X	X				X	X	X			X			X	X	X	X																		X
	Imaginary Pinnacle				X				X	X				X			X	X	X	X															X			X
Conservation																																						
	CAM Plants					X			X	X				X			X						X					X				X	X					
	Imaginary Pinnacle					X			X	X				X			X						X					X				X	X					

For each individual challenge, the dominant features of the corresponding pinnacles in each category are indicated in the grey-shaded line at the bottom of each challenge section. For example, the two chosen pinnacles for the water gain challenge, i.e., the Thorny Devil and the Namib beetle, both share the scale micro. Therefore, the dominant scale feature for the water gain challenge is micro as well. In a case of undetermined dominant feature of a specific category (e.g., environmental context for water loss), the category lists all its features for possible design solutions (e.g., arid, tropical, moderate, and continental). If no features are identified for the category (e.g., morphological features for water loss) then the category is irrelevant for the design concept corresponding to the challenge. In summary, the main objective of the pinnacle analysing matrix presented in Table 6.2 is to determine the dominant features of each challenge of the design concept. In the given example there are maximum of three pinnacles for a challenge (i.e., transportation). The example provides an illustration for the technique for obtaining the dominant features of each challenge. In that respect, it is notable that increasing the pinnacle sample size would result in more reliable dominant features.

The design path matrix (Figure 6.17) represents the superposition of the imaginary pinnacles for water gain, transportation, loss, and conservation, in order to determine the dominant features to be addressed in the integrated design concept. The dominant features (the orange nodes) are the features that have the larger number of connections from the different imaginary pinnacles (different path colours), where the larger the number of connections (counting colours) the more dominant the feature becomes.

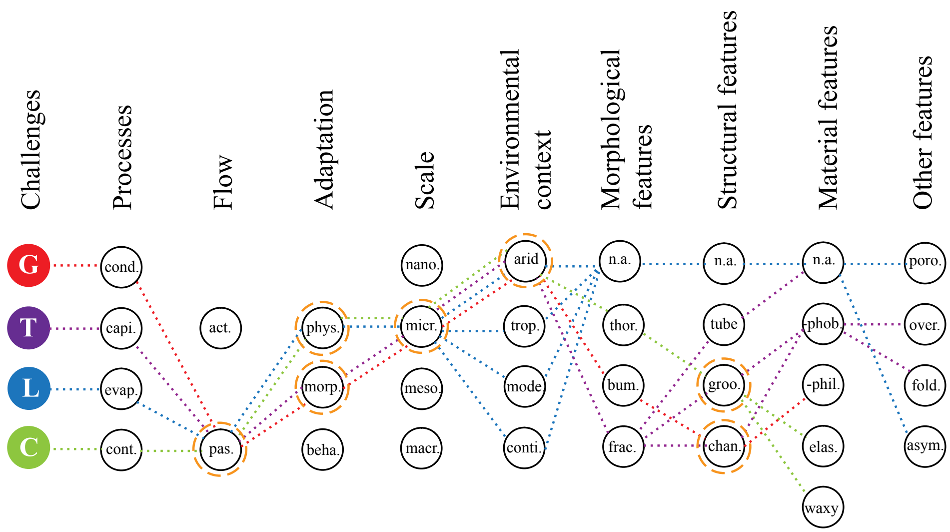


Figure 6.17 ....

Design path matrix. Each vertical column represents a category and its various features. Red lines denote the path of water gain, purple line denote the path of water transportation, blue lines denote the path of water loss, green lines denote the path of water conservation, and the orange nodes denote the dominant features which represent the design path.

The design path matrix for water gain, transportation, conservation and loss indicates several features/properties from the various categories relevant for the design concept:

- Condensation of gain, capillary action for transportation, evaporation for loss, and control permeability for conservation
- The flow is passive for all functions
- The adaptation type is physiological for water gain and conservation, and morphological for water transportation and loss
- The micro scale is the relevant scale for all functions
- The imaginary pinnacles share arid environmental context
- The morphological features are independent for each specific function
- The structural features are: grooves for water transportation and conservation, and channels for water gain and loss
- The other related features potentially to be addressed in the context of processes are: porosity, overlaps, folding, and asymmetric expansion

Besides the derived dominant features, the design path matrix indicates potential physical relationships of the design concept. For example, under the category of Adaptation two dominant features are distinguished, which may indicate for a potential integration of elements in the design concept. In the case, where no dominant feature is distinguished, i.e. the category of morphological features; each feature has to be related to the corresponding process in the design. The illustration of the transformation of the design path matrix into a design concept is elaborated in the next section, and a potential outcome is presented.

6.4.5 Preliminary design concept proposal (step 5)

The first step of the transformation of the design path matrix into a design concept is an abstract graphical translation that incorporates the various features/properties and relationships. The challenges are presented through the corresponding processes, and translated into graphical elements emphasizing features and relationships, as presented in Figure 6.18.

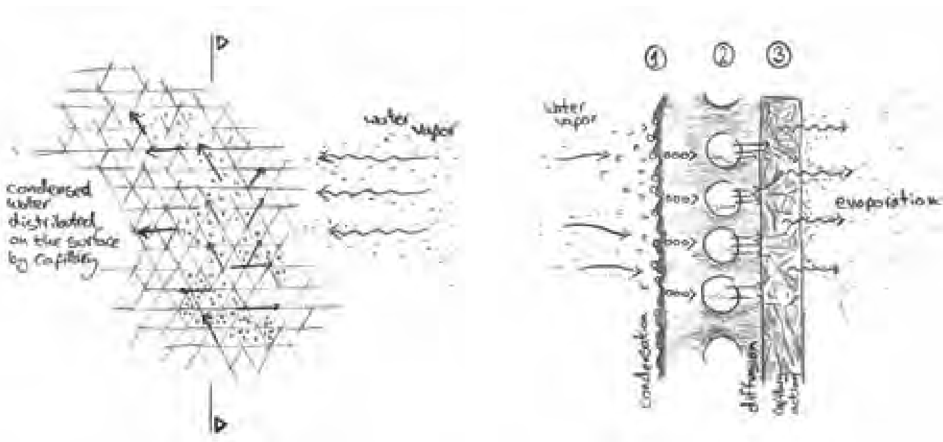


Figure 6.18

Abstract graphical representation of the design concept. Right (cross section): (1) the most outer layer collects water by vapor condensation, distribute water on the surface by capillary action (left: front view), and transports the collected water to (2) the second layer, where water is stored and conserved. (3) the inner most layer is a porous medium that absorbs water from storage and allows evaporation to the interior spaces passively.

Recall that the Namib Beetle is able to collect water from fog, which is collected on the elytra through condensation, and directed to its mouth. The water harvesting surface of the design concept is based on the special geometry of the elytra that enables the Beetle to attract water. It consists of an array of mounds, where the surface is a combination of hydrophilic and hydrophobic regions. Each mound consists of grooves and peaks; water droplet sticks to the hydrophilic peaks and build up until they reach a specific size and roll down through the hydrophobic grooves. The mounds are surrounded by micro channels, which create a hexagonal network to transport water over the surface via capillary action. These micro channels in the design are inspired from the Thorny Devil's semi tubular capillary system, which are the main feature of its special integument, allowing it to transport water to the mouth. The water is stored in the cavity in numerous independent containers, which are connected to a fibrous material (in contact with the indoor spaces) that absorbs water from the container and allows evaporation. While the water is collected throughout the night, it is released throughout the dry or hot days for humidification or cooling and increased occupant comfort.

The system is passive, where each integrated element has its own function and at the same time contributes to the overall performance simultaneously. The design concept adapts its characteristics from the proven strategies and mechanisms of nature. The most outer surface of the design, which is responsible for water gain (Figure 6.19), adapts the morphological features of the bumpy elytra of the Namib beetle, and features hydrophilic and hydrophobic alternating properties of bumps and grooves (respectively). Numerous bumpy mounds create the outer surface, where micro grooves (adapted from the thorny devil) separate them from each other and create a hexagonal network (Figure 6.20 left). These micro grooves are responsible for transporting water over the surface when closed via capillary action, or channeling water to the storing chambers (located in the cavity) when opened via gravity (Figure 6.20 right). The opening and closing of the storing chambers are controlled by passive elements, possibly made of smart materials, (adapted from stoma, human skin, and CAM plants), which swell when fully saturated (Figure 6.21 right), and shrink when dry (Figure 6.21 left), thus allowing water absorption to the inner evaporative surfaces. The wet surfaces allow evaporation to the interior spaces and contribute in humidifying the air and increased comfort. Since the mechanisms of the design concept were extracted from nature that share the same challenge, and no scaling has been made (from the original Pinnacles), it is expected that the same physical rules will act on the design concept.

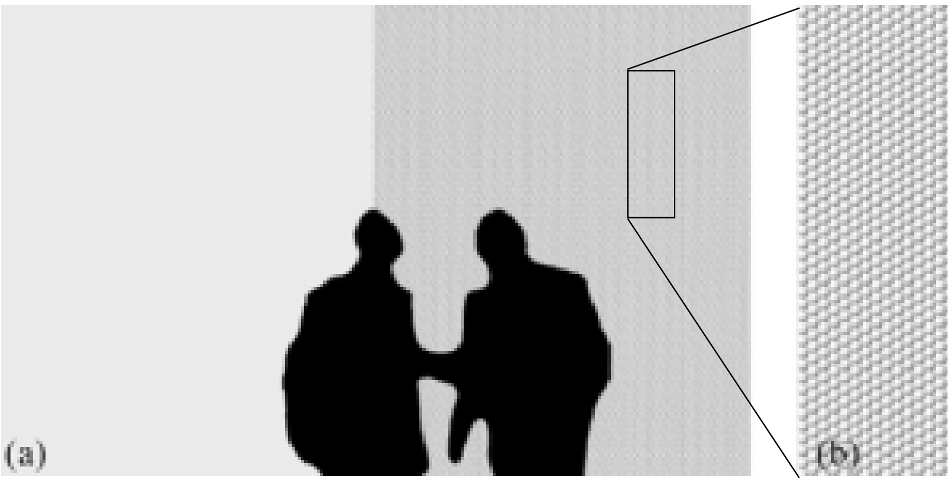


Figure 6.19

The water harvesting surface. (a) Exterior view of the water harvesting surface applied on the building envelope. (b) Scaled up view, showing the general bumpy texture of the surface.

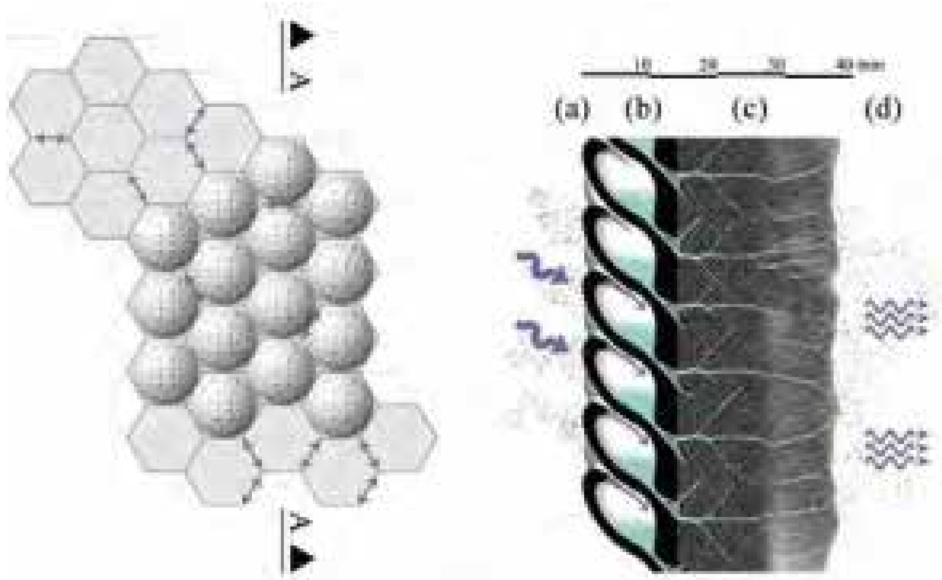


Figure 6.20

The water harvesting system. Left: front view of the bumpy mounds and the grooves generated between the mounds to exhibit capillary action to distribute water over the surface. Right, cross-section AA: (a) water droplets are attracted to the bumpy surface, where they build up and run down towards the grooves. (b) When the grooves are at the open state, then water falls to the storing chambers, otherwise water is distributed over the surface and fall in the closest storing chamber. (c) Controllable outlet of the storing chamber is connected to a fibrous material that absorbs water via capillary action through a fractal network, (d) and allows evaporation to the interior spaces.

Figure 6.21

Left – grooves at open state: the storing chambers are not full with water, and the evaporative surface is not fully saturated. Right – grooves at closed state: the evaporative surface is fully saturated, which causes swelling to the flexible component (grey cell) and expanding to block the canal leading to the evaporative surface and avoid further absorption. As the chamber gets full with water the upper flexible components (grey cells) swell and expand towards the position of the flexible material (marked in red), and result in the closure of the storing chambers.

6.4.6 Estimation of performance

A simplified equation is developed for the estimation of performance. The efficiency of the building envelope can be estimated by the number of days, *N*, per year the envelope provides a comfort level of humidity in the interior of the building, which can be calculated by the proposed performance equation

$$N = \frac{c \cdot S \cdot n_f}{V \cdot n_a \cdot AH}$$

where *c* is the weight of the collected water per surface area per fog event (2 hours), *S* is the total surface of the envelope, n_f is the number of fog events per year, *V* is the volume of the interior, n_a is the frequency of air exchanges (per day), and *AH* is the desired absolute humidity. It is assumed that the exchanged air is absolutely dry, and the evaporation rate is relatively high and controlled to prevent over humidification. With these assumptions the performance equation provides low limit estimation (minimum number of days). The performance equation successfully predicts that decreasing the surface area of the envelope or increasing the volume of the interior or the desired humidity reduces the number of days of which the envelope can humidify the interior at the required level.

As an example, take a 3x3x3 m^3 room (V=27 m^3), and an envelope of 3x3 m^2 (S=9 m^2). A comfort level of relative humidity is within a range of 25%-60%. In arid areas the lower level of the relative humidity range (25%) is likely the target. A 25% relative humidity can be converted to absolute humidity units using a standard climate humidity table, which is AH = 7.6 gr/m^3 at 30º C. The rate of air exchange is assumed to be once per hour (n_a = 24 per day) for efficient ventilation. The number of fog events in the Namib Desert is n_f = 30 per year. Following Nogaard and Dacke [2010] a Namib beetle positioned head down at an angle of 23º in a fog chamber is able to collect, on average, about 0.1 ml of water per hour. The beetle has a surface area of about 1 cm^2 which is equal to the area of each collection unit of the design concept. Assuming that the fog event lasts for only two hours yields c = 0.2 gr/cm^2. Substituting in the performance equation yields N = 109 days per year. This implies that the envelope is able to humidify the interior during about one third of the year. Note that in coastal regions there are more than 180 days of thick fog a year, which guarantees humidification of the interior during all days of the year using a smaller envelope area relative to the interior volume.

6.5 Conclusions

Water regulation mechanisms found in nature were investigated with the objective of implementation in building envelopes based on the living envelope methodology (chapter 3). An example for generating a design concept for a water harvesting (for the purposes of humidifying) envelope was presented. The envelope is a passive system that collects water from vapour via condensation at dawn, disperses the water over the surface, or channels the collected water to storing chambers, and releases the water to the inner evaporative surfaces for humidification. An estimation on the envelope performance showed that the envelope is capable to achieve interior comfort levels of relative humidity at 25% for at least 3 times the number of fog days for an arid region.

The initial investigation was summarised in an exploration model flowchart for water regulation (section 6.3), which provides a navigation tool to outline exemplary pinnacles corresponding to defined design challenges. The exploration model bridges between gained information on water gain, conservation, transportation, and loss, found in nature, and the aimed water regulation challenges of the building envelope – water harvesting for humidification of the interior. Furthermore, the exploration model indicates whether to investigate a specific group of pinnacles or to manipulate the physical properties of the environment, which could assist in narrowing the broad range of possibilities throughout the design process.

The pinnacle analysing matrix (Table 6.2), and the design path matrix (Figure 6.17) have flexible input (various inputs of water regulation challenges and pinnacles), yet they have selective output (dominant water regulation features are sought). As a result, these tools increase the efficiency of the design process. In the current chapter, six pinnacles have been selected in the exploration model, with the objective to achieve four functions – water gain, transportation, distribution, and loss. Some of the pinnacles where selected under more than one function (e.g., the Thorny Devil and the Namib beetle where selected for water gain and transportation). It is obvious that in general the probability of achieving a dominant feature increases with the sample pinnacles size. In the presented example there are 23 pinnacles, in total, corresponding to the four required functions. However, the selection of the relevant processes decreases the number of analysed pinnacles into six (some with multiple functions), and thus reduces the complexity of achieving an imaginary pinnacle (and the lengthy process of analysing selected pinnacles). Thus, while the sample size is important, the sub selection of pinnacles based on processes and factors, and thus reducing the sample size, is favourable. It is also remarkable that wide experience and knowledge of existing pinnacles, as well as technical demands and requirements, such as accessible technology, assist the selection of "promising" pinnacles. Moreover, applying large numbers of relevant pinnacles in the design path matrix phase may result in multiple solution paths based on different dominant features. Each solution path may lead to a different design concept. Integration of multiple solution paths into one component is achievable only if the dominant features of each solution are insensitive to (or integrable with) the existence of the dominant features of the other solutions (e.g., the morphological features are independent of each other). In this case the component is referred to as multi-functional.

The result of the exemplary design concept shows the remarkable advantage of the living envelope methodology for the design of water regulation envelopes. The methodology is capable to generate a design concept with specified initial challenges. Although the applied living envelope methodology somewhat limits the design degree of freedom, in terms of choosing the dominant features of the selected pinnacles, of each challenge, it provides a certain degree of freedom to choose the processes, factors, and the corresponding pinnacles, as well as it allows further extension of the exploration model at all levels. As a result, various innovative design concepts may arise.

References

Al-Jayyousi, O.R., [2003]. Greywater reuse: towards sustainable water management. *Desalination*, 156(1-3), pp. 181-92.

Alvarez, J.M., Rocha, J.F., and Machado , S.R. [2008]. Bulliform Cells in Loudetiopsis chrysothrix (Nees) Conert and Tristachya leiostachya Nees (Poaceae): Structure in Relation to Function. *Braz. arch. biol. technol.*, **51**(1), pp.113-119,

Aylor D.E., Parlange, J.Y., and Krikorian, A.D., [1973]. Stomatal mechanics. *Am J Bot* , **60**, pp. 163-171.

Atwell, B.J., Kriedemann, P.E., & Turnbull, C.G.N., [1999]. *Plants in Action: adaptation in nature, performance in cultivation*, South Yarra: Macmillan Publishers.

Bar-Cohen, Y. (ed.), [2006]. *Biomimetics: Biologically Inspired Technologies*, Boca Raton: CRC Press.

Beetle-based water harvesting, available online at: http://www.rexresearch.com/qinetiq/qinetiq.htm (retrieved July 2011).

Bentley, P.J. & Blumer, W.F.C., [1962]. Uptake of water by the lizard, Moloch horridus. *Nature*, **194**, pp. 699-700.

Blonder, B., Violle, C., Bentley, L.P., and Enquist, B.J., [2011]. Venation networks and the origin of the leaf economics spectrum. *Ecology Letters*, **14**(2), pp. 91-100.

Bjorn, L.O. & Govindjee, G., [2008]. *The Evolution of Photosynthesis and Its Environmental Impact Photobiology*, New York: Springer.

Brian Chiu [2007], *Lepidochora discoidalis*, ECOgarden, available online at: http://www.flickr.com/photos/ecogarden/2082676399/in/photostream/ (retrieved August 2012).

Capillary Action, available online at: http://science.jrank.org/pages/1182/Capillary-Action.html (retrieved April 2011).

Chapa, J., [2007]. CH2: Australia's greenest building. Available online at: http://inhabitat.com/ch2-australias-greenest-building/ (retrieved July 2011).

Comanns, P., Effertz, C., Hischen, F., Staudt, K., Bohme, W., and Baumgartner, W., [2011]. Moisture harvesting and water transport through specialized micro-structures on the integument of lizards. *Beilstein Journal of Nanotechnology*, **2**, pp. 204-214.

Crawford, C.S., [1981]. *Biology of Desert Invertebrates*, Berlin: Springer.

Dixon, A., Butler, D., Fewkes, A. [1999]. Water saving potential of domestic water recycling systems using greywater and rainwater in combination. *Water Science and Technology*, **39**(5), pp. 25–32.

Fewkes, A., [1999]. The use of rainwater for WC flushing: the field testing of a collection system. *Building and Environment*, **34**(6), pp. 765-72.

Fitter, A.H. & Hay, R.K.M. [2002]. *Environmental Physiology of Plants*, London: Academic Press.

Fitting, H., Harder, R., Schumacher, W., and Firbas, F., [1950]. *Lehrbuch der Botanik fur Hochschulen*, Stuttgart: Pscator.

Forslind, B. & Lindberg, M., [2004]. *Skin, Hair, and Nails: Structure and Function*, Basel: Marcel Dekker.

Franks, P.J. & Farquhar, G.D. [2007]. The Mechanical Diversity of Stomata and Its Significance in Gas-Exchange Control. *Plant physiology*, **143**, pp. 78-87.

George Shuklin [2007]. *Water droplets on spines of cactus*, available online at: http://commons.wikimedia.org (retrieved August 2012).

Giurgiutiu, V., Matthews, L., Leo, D.J., & Sundaresan, V.B. [2005]. Concepts for Power and Energy Analysis in Nastic Structures. *ASME Conference Proceedings*, 2005, pp. 421-428.

Goniakowska-Witalinska, L. & Kubiczek, U., [1998]. The structure of the skin of the tree frog (Hyla arborea arborea L.). *Annals of Anatomy*, **180**, pp.237-246.

Govindjee, Beatty, J.T., Gest, H., and Allen, J.F., eds. [2005]. *Advances in Photosynthesis and Respiration: Discoveries in Photosynthesis*, Dordrecht: Springer.

Hamilton, W.J. III & Seely, M.K., [1976]. Fog basking by the Namib Desert beetle, Onymacris unguicularis. *Nature*, **262**, pp. 284-285.

Henderson, V. [2012]. Tomato leaf curl. *Vicki's garden*, available online at: http://vickisgardentips.com/?p=593#comments

Herrmann, T., Schmida, U., [1999]. Rainwater utilisation in Germany: efficiency, dimensioning, hydraulic and environmental aspects. *Urban Water*, **1**(4), pp. 307-316.

Hill, R.W., Wyse, G.A., and Andreson, M., [2008]. *Animal Physiology*, Massachusetts: Sinauer Associates Inc.

Jaeger, E.C. [1957]. *The North American Deserts*, Stanford: Stanford University Press.

Jim Conrad [2008]. *A sweetgum (Liquidambar styraciflua) leaf*, available online at: http://commons.wikimedia.org/wiki/File:Sweetgum-domatia.jpg (retrieved August 2012).

Kaldari [2009]. *Giant barrel cactus (Echinocactus platyacanthus)*, available online at: http://commons.wikimedia.org/wiki/File:Kaldari_Echinocactus_platyacanthus_01.jpg (retrieved August 2012).

Katifori, E., Szollosi, G. J., and Magnasco, M., [2010]. Damage and Fluctuations Induce Loops in Optimal Transport Networks. *Physical Review Letters*, **104**(4): 048704.

Lancaster, J., Lancaster, N., and Seely, M.K., [1984]. Climate of the central Namib Desert. *Madoqua*, **14**, pp. 5-61.

Louw, G.N., [1972]. The role of advective fog in the water economy of certain Namib Desert mammals. *Symosia of the zoological society of London*, **31**, pp. 297-314.

Lynne Jenkins [2009]. *Structure*, available online at: http://www.flickr.com/photos/carolinashots/4069076089/ (retrieved August 2012).

Martorell, C. & Ezcurra, E. [2007]. The narrow-leaf syndrome: a functional and evolutionary approach to the form of fog-harvesting rosette plants. *Oecologia*, **151**, pp. 561-573.

Moulia, B. [1994]. The biomechanics of leaf rolling. *Biomimetics*, **2**, pp. 267-281.

Murrish, D.E. & Schmidt-Nielsen, K. [1970]. Exhaled air temperature and water conservation in lizards. *Respiration Physiology*, **9**, pp. 263-276.

Nastic Structures, available online at: http://www.che.sc.edu/centers/RCS/matthews/index.htm (retrieved April 2011).

Nobel, P.S., [1988]. *Physicochemical and environmental plant physiology*, San Diego: Academic Press.

Nørgaard, T. & Dacke, M., [2010]. Fog-basking behaviour and water collection efficiency in Namib Desert Darkling beetles. *Frontiers in Zoology*, **7**(23).

Olivier, J. & de Rautenbach, C.J,, [2002]. The implementation of fog water collection systems in South Africa. *Atmospheric Research*, **64**, pp. 227-238.

Parker, A.R. & Lawrence, C.R., [2001]. Water capture by a desert beetle. *Nature*, **414**, pp. 33-34.

Paturi, F.R. [1976]. *Nature, Mother of Invention: The Engineering of Plant Life*, London: Thames and Hudson.

Peterson, J.A. [1984]. The microstucture of the scale surface in iguanid lizards. *J Herpetol*, **18**, pp. 437-467.

Quere, D. [2008]. Wetting and Roughness. *Annual Review of Materials Research*, **38**, pp. 71–99.

Randall, W.C., [1946]. Quantitation and regional distribution of sweat glands in man. *Clinical Investigation*, **25**(5), pp. 761-767.

Randall, W.C., [1947]. Local sweat gland activity due to direct effects of radiant heat. *American Journal of Physiology*, **150**, pp. 365-371.

Roberts, A., Plant Anatomy – Glossary. Available online at: http://www.uri.edu/cels/bio/plant_anatomy/glossary.html (retrieved September 2012).

Robinson, C. [2009]. Capillary Action http://www.wtamu.edu/~crobinson/SoilWater/capillar.html, (retrieved April 2011).

Rockefeller University [2010, March 3]. Leaf veins inspire a new model for distribution networks. *ScienceDaily*, available online at: http://www.sciencedaily.com / releases/2010/02/100227214036.htm (Retrieved October 6, 2012).

Rushmer, R.F., Buettner, K.J.K., Short, J.M., and Odland, G.F., [1966]. The skin. *Science*, **154**, pp. 343-348.

Schmidt-Nielsen, K., [2007]. *Animal physiology: adaptation and environment*, New York: Cambridge University Press.

Schmidt-Nielsen, K., Hainsworth, F.R., & Murrish, D.E. [1970]. Counter-current heat exchange in the respiratory passages: effect on water and heat balance. *Respiration Physiology*, **9**, pp. 263-276.

Schmidt-Nielsen, K., Taylor, C.R., & Shkolnik, A. [1971]. Desert Snails: Problems of Heat, Water and Food. *Journal of Experimental Biology*, **55**, pp. 385-398.

Seely, M.K. & Hamilton, W.J. III, [1976]. Fog catchment sand trenches constructed by Tenebrionid beetles, Lepidochora. from the Namib Desert *Science*, **193**, pp. 484-486.

Sherbrooke, W.C. [1990]. Rain-harvesting in the lizard, Phrynosoma cornutum: behavior and integumental morphology. *J Herpetol*, **24**, pp. 302-308.

Sherbrooke, W.C. [2004]. Integumental water movement and rate of water ingestion during rain harvesting in the Texas horned lizard, Phrynosoma cornutum. *Amphibia-Reptilia*, **25**, pp. 29-39.

Sherbrooke, W. Scardino, A. de Nys, R., and Schwarzkopf, L., [2007]. Functional morphology of scale hinges used to transport water: convergent drinking adaptations in desert lizards. *Zoomorphology*, **126**(2), pp. 89-102.

Stan Shebs [2006]. Agave flexispina at the University of California Botanical Garden, available online at: http://commons.wikimedia.org/wiki/File:Agave_flexispina_2.jpg (retrieved august 2012).

Stolz, G.M. [2008]. Peyote Cactus. *U.S. Fish and Wildlife Service*, available online at: http://commons.wikimedia.org/wiki/File:Peyote_Cactus.jpg (retrieved August 2012).

Strain, D. [2011]. Australian Frogs Do the Dew. *Sciencemag*, online at: http://news.sciencemag.org/sciencenow/2011/09/australian-frogs-do-the-dew.html (retrieved February 2012)

Sue Winkler [2011]. *Dehydrated cacti*, available online at: http://www.flickr.com/photos/azsue22/5521106943/ (retrieved July 2012)

Summers, A. [2004]. Like water off a beetle's back. *Biomechanics*, online at: http://www.nhmag.com/biomechanics/171934/like-water-off-a-beetle-s-back (retrieved July 2011)

Superhydrophobia is perfectly natural [2008]. R&D Magazine, online at: http://www.rdmag.com/Awards/RD-100-Awards/2008/09/Superhydrophobia-Is-Perfectly-Natural/ (retrieved July 2011)

Thorny Devil, available online at: http://www.vincelewis.net/thornydevil.html (retrieved April 2011)

Thurow, T.L., Chapter 6 – Hydrology and Erosion, available online at: http://cnrit.tamu.edu/rlem/textbook/Chapter6.htm (retrieved July 2012)

Topinambour [2004]. *Lanzarote Cacti*, available online: http://www.flickr.com/photos/topinambour/124638553/ (retrieved July 2012)

Vecchia, F.D, El Asmar, T., Calamassi, R., Rascio, N., & Vazzana, C. [1998]. Morphological and ultrastructural aspects of dehydration and rehydration in leaves of Sporobolus stapfianus. *Plant Growth Regulation*, **24**, pp. 219-228.

Ward, J.D., Seely, M.K., and Lancaster, N., [1983]. On the antiquity of the Namib. *South African Journal of Science*, **79**, pp. 175-183.

Weaire, D. & Rivier, N. [1984]. Soup, cells and statistics – random patterns in two dimensions. *Contemporary Physics*, **25**(1), pp.59-99.

Wong, T.S., Kang, S.H., Tang, S.K.Y., Smythe E.J., Hatton, B.D., Grinthal, A., and Aizenberg, J., [2011]. Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity. *Nature*, **477**(7365), pp. 443-447.

Light

Chapter 7

7.1 Introduction

Building envelopes might be exposed to various amounts of light (solar radiation) that has to be managed continuously due to dynamic changes of light intensity and interception (i.e., transmission or absorption). Managing light becomes a real challenge when several elements are considered simultaneously, e.g. maximizing daylight, while optimising solar gain, yet considering glare. The use of thermochromic coatings on glass can influence transmission properties in response to temperature, and result in reduced energy consumption in buildings [Parkin & Manning 2006, Saeli *et al.* 2010]. Yet, the common solution for managing light is a shading system.

Shading systems are attached to buildings in order to control the amount of radiation on the envelope for reducing heat loads, while providing a visual contact with the exterior environment. Current shading technologies deal, primarily, with extensions either vertically or horizontally, or by adding an extra cladding to protect against radiation from glazed openings. Other solutions, based at the molecular level, have also emerged to control the amount of light penetrating inside, e.g. reflective and selective coatings, and thermo-chromic glass [Compagno 2002].

Although the majority of shading devices used in buildings have limited adjustability, as they are designed to react to the extreme situations of solar radiation and not for the whole exposure of solar radiation, numerous innovative shading solutions have been emerging to provide shading as a response to radiation variations. For example, the shading elements of Singapore Lyceum Theatre are distributed all over the structure (Figure 7.1). The intention of the architects (DP Architects) was, that the enveloping facade system changes pattern to suit the orientation, providing solar shading and controlling the internal environment of the pavilions [Siek 2001]. The structural geometry was inspired from nature, like sunflowers, durian, etc. In this particular case, located at the equator region, each shading device is not adjusting itself throughout the day or seasons since sun-ray angles don't change dramatically. The study of the location (latitude) and climate conditions influences the design of the effective shading system [Hausladen *et al.* 2006].

Figure 7.1

The shading cladding of the Singapore Lyceum Theatre.

Nowadays, emerging approaches of creating dynamic patterns for the adaptive shading devices can be found, with the aim to manage light intensity and interception. For example, parametric design tools have been developed to find the relationships between geometry and performance for the generation of climate adaptive shading skins [e.g. Turrin *et al.* 2011]. Biomimetic approaches for concept generation may also result in kinetic structures that create dynamic shading. A recent analysis of the functional-morphological features of plant movement has resulted in the generation of a deployable surface for a shading device (Figure 7.2), which creates an innovative dynamic pattern in the shading lamella [Lienhard *et al.* 2011].

Responding to light is one of the common abilities of many forms of life [Land 2005]. "Living organisms use light as a source of energy and as a means of obtaining information about their environment" [Presti & Delbruck 1978]. The rotation of sun and earth create unique light habitats on earth, where organisms have adapted various strategies and mechanisms that can manage light intensity and interception.

In section 7.2 of the current chapter several light regulation strategies in nature are presented, with a focus on light intensity and interception management. The relevant processes, function, factors, and pinnacles for light regulation are summarized in a flow chart of the exploration model in section 7.3. An example of a design concept generation for a system that manages radiation intensity is presented in section 7.4, where an estimation of performance is given. Finally, the concluding remarks are given in section 7.5.

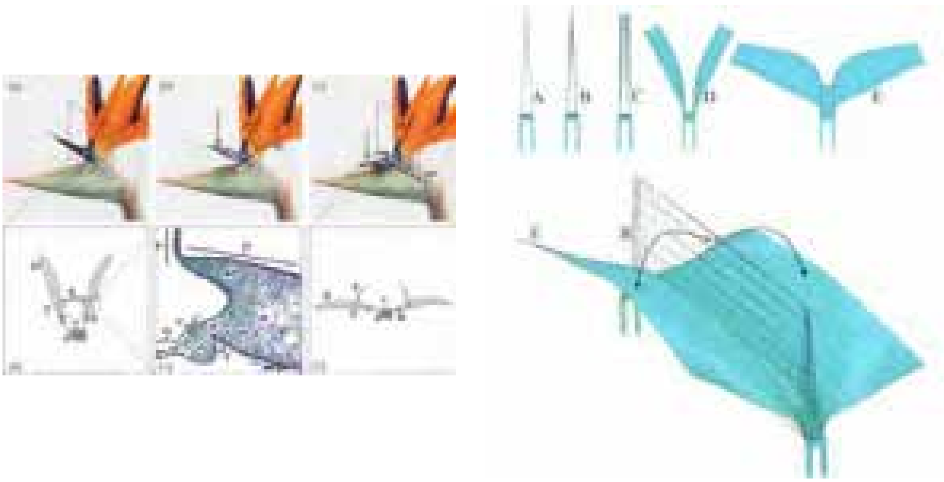


Figure 7.2

Left: the shading lamella inspired by the valvulr pollination mechanism in the *Strelizia reginae* flowers (bird-of-paradise). Right: Illustration of a double Flectofin ® - (A) Theoretical position of the planar wings, (B) real position of the wings pushing against each other and (C)–(F) opening of the wings due to bending of the backbone. Images provided by Julian Lienhard [Lienhard *et al.* 2011].

7.2 Light regulation in nature

Solar radiation is the main source of light. It is a transient state changing throughout the various time scales (i.e., hours, days, and seasons), where the sun orientation (angle of incidence) and weather conditions influence light intensity and interception.

For living organisms in general, and plant in particular, light intensity is important, among others, for the conversion of light into energy (e.g. photosynthesis). The more perpendicular the angle of incidence is (determined by sun path and orientation) and the clearer the sky is the higher the intensity of light becomes (clouds scatter/diffuse light hence reduce its intensity). Therefore, organisms, and in particular plants, have developed numerous mechanisms and strategies to manage light intensity. On the other hand, managing light interception is significant for optimized information gain from the surrounding and adequate response. To this end, organisms have developed various techniques to control and regulate light interception.

Exploring and learning from the strategies and techniques developed by nature for managing light intensity and interception is significant for implementation in building envelopes, where similar conditions and requirements may rise. Further details on light intensity and interception are given in the following sections.

7.2.1 Light intensity management

Managing light intensity depends on the source, the medium, and management processes by organisms (e.g. plants). The current section presents three major processes in managing light intensity: (1) exposure, with a focus on structure and area; (2) inclination, in particular light tracking leaf orientation; and (3) diffuse reflection.

7.2.1.1 Exposure

Plants need solar radiation for photosynthesis and plant productivity, where they tend to maximize exposure to radiation. The geometric structure has a great impact on plants in nature [Takenaka *et al.* 1998]. Morphological and physiological factors influence light interception in plants [Brunig 1976]. Thus, these affect photosynthesis and rate of plant productivity [Loomis *et al.* 1971]. Leaf special arrangement and leaf density are factors that affect distribution in plants for efficiency. They affect and reduce the ability of solar tracking at the plant canopy [Ehleringer & Forseth 1980]. Plant planar area, angle of incidence, and distribution play a significant role in influencing the exposure to sun radiation.

Structure

Generally, leaves are flat and thin structures; their main purpose is to expose the cells containing chloroplasts to sunlight for photosynthesis. Form, proportion, and angle of incidence are three of the main factors for efficiency [Kriegh & Kriegh 2003]. Some plants have special geometrical arrangements that can be described mathematically[1], e.g.

1 Mathematical description of geometrical arrangements such as the Fibonacci pattern is of great interest in implementation in architecture, due to the convenient reproduction ability.

Fibonacci series found in understory plants with low light conditions; these arrangements are adopted for compact and dense packing of leaves in order to maximize light exposure. The Fibonacci pattern could be applied in two or three dimensions. In Figure 7.3, the Fibonacci pattern is applied, where leaves grow in size but they don't change their shape. In the illustration, a two dimensional and horizontal growth is maximized by adopting the Fibonacci series, which packs a maximum amount of elements in the minimum area, and results in efficient maximised exposure to light.

Figure 7.3

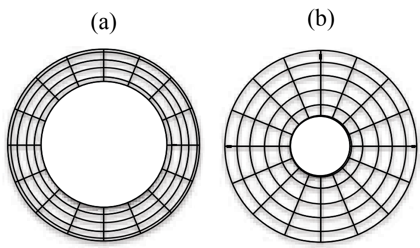
Aeonium tabuliforme is a succulent forming a compact flat rosette of overlapping leaves. This arrangement applies Fibonacci pattern for compact horizontal growth and packing for maximum light exposure.

Area

The pupil of the human eye, which allows the light to enter, is surrounded by an adaptive muscle called the iris. According to Hooker [1865], the iris makes the pupil larger or smaller in order to regulate light intensities. He explains that the iris contains a set of radial and circular fibres to regulate the dilation of the pupil (Figure 7.4). When the pupil is wide open (dim light) the circular fibres of the iris are relaxed while the radial ones are contracted, Figure 7.4a. When the pupil is small (bright light), the radial fibres of the iris are relaxed while the circular ones are contracted, Figure 7.4b [Hooker 1865].

Figure 7.4

Deformation of the human pupil. On the left (a) the pupil is wide open (dilated) while on the right (b) the pupil is contracted. After Hooker [1865].



7.2.1.2 Inclination

Plasticity in response to sunlight is one of the dominant aspects of plant architecture [Pearcy *et al.* 2005]. This plasticity is recognized when leaflets shift from a vertical position to a horizontal position. This process includes: "*increased internode and petiole lengths, and increased leaf size but decreased leaf mass per unit area in shade vs sun shoots*" [Pearcy *et al.* 2005]. Dynamics in plants are generated due to their nastic *structure*[2] [Bar-Cohen 2006]. "*Regulation of leaf orientation is a complex response that is dependent on successful integration of multiple photoreceptors, hormonal signals and gating by the circadian clock*" [Mullen *et al.* 2006]. There exist three categories of leaf reorientation [Darwin 1880]:

- Nyctinastic (sleep movements)
- Seisonastic (movements in response to shaking)
- Heliotropic (leaf movements tracking the sun)

"*Heliotropism is the movement of leaves following the sun and is of two types: diaheliotropism and paraheliotropism. The movement of blades of diaheliotropic leaves is such that they remain perpendicular to the sun's direct rays throughout the day. The movement of blades of paraheliotropic leaves is such that they remain parallel to the sun's direct rays.*" [Ehleringer & Forseth 1980]. Heliotropism (sun-tracking) is one of the ways to regulate light intensity on the surface: "*leaves that are perpendicular to the sun's direct rays for tracking appear to have high photosynthetic rates throughout the day, whereas leaves parallel to the sun's rays have reduced leaf temperatures and transpirational water losses.*" [Ehleringer & Forseth 1980]. For example, sunflowers track sun path throughout the day by bending towards light and maintaining radiation perpendicular to surface [Shell *et al.* 1974]. Heliotropism is a nastic response, where motor cells located at the base of the bud enlarge or shrink in response to turgor pressure [Kiosawa & Tanaka 1976]. The blue wavelength of light increases potassium concentration in the motor cells, thus decreases osmotic pressure; as a result, the cells absorb more water and elongate to bend towards the sun [Hader & Lebert 2001].

Plants tend to vary their inclinations in order to regulate light interception according to different climates. At hot and dry climates plants' leaves face east, maximizing light interception in the early morning and late afternoon while keeping a minimum interception at noon [Ezcurra *et al.* 1991]. Uniformly distributed leaves in all azimuthally directions with a steep inclination, have a relative well performance in all seasons at all hours of the day, where high leaf angles reduce noon canopy heat-loads in dry regions [King 1997]. Leaves' becoming more vertical is a method for protection from over exposure of sunlight [King 1997, Falster & Westoby 2003]. Leaves facing north (in regions at southern hemisphere, e.g. Argentina) acquire a gradual warming during the morning and gain maximum light at winter noon's [Ezcurra *et al.* 1991].

2 Nastic structure consists of "motor cells that swell in size and act like muscles to cause local tissue expansion, causing bending deformation and overall plant tissue rotational or translational displacement" [Matthews & Giurgiutiu 2006].

According to Mullen *et al.* [2006], when the environment of the leaves changes from dark to light the leaves change their inclination to a more horizontal situation. Faster reorientation was reported when plants were placed in a darker place than when they entered darkness at the end of the day [Mullen *et al.* 2006]. Leaf movement can be recognized in reorientation from a horizontal to a vertical position at night [Satter 1979]. More constant and lower inclinations of leaves were reported at cloudy days than sunny days [Barradas *et al.* 1999].

7.2.1.3 Diffuse reflection

Diffuse reflection of light is the scattering of an incident light by a surface or a medium (e.g. clouds). The general mechanism of diffuse reflection is illustrated in Figure 7.5. Diffuse reflection, and in particular, the scattering of light from objects, is the major process causing the vision of these objects by organisms' eyes.

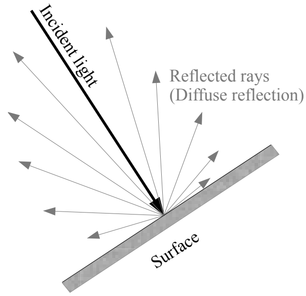


Figure 7.5

An illustration of the general mechanism of diffuse reflection of light.

Some organisms are able to release pigments in the cornea (the transparent layer of the eye) when encountering excessive light. For example, the balloon fish has iridescent eyes, which means that certain wavelengths of light can pass through the eye, whereas other are strongly reflected in glittering colours. The balloon fish (Figure 7.6), among other shallow water fish, can release yellow pigments (a reversible process) in cornea to filter light intensity [Appleby & Muntz 1979]. This yellow pigment absorbs and reflects a significant part of the light and therefore reduces the light intensity on the retina of the fish [Orlov & Gamburtzeva 1976, Orlov & Kodrashev 1998, Collin & Collin 2001, Yahya 2000].

Figure 7.6

Left: Baloonfish, courtesy of Nhobgood Nick Hobgood [2008]. Right: yellow pigment release, courtesy of Kevin Briant [2010].

7.2.2 Light interception management

Some organisms manage light interception and reduce glare from the surrounding surfaces via transmission, or absorption, e.g. for better visual conditions. The structures of the surface of incidence as well as pigments are among the factors that have a great influence on the management of light interception. The following provide examples on organisms that manage light interception via light transmission, refraction, reflection, and absorption.

7.2.2.1 Transmission

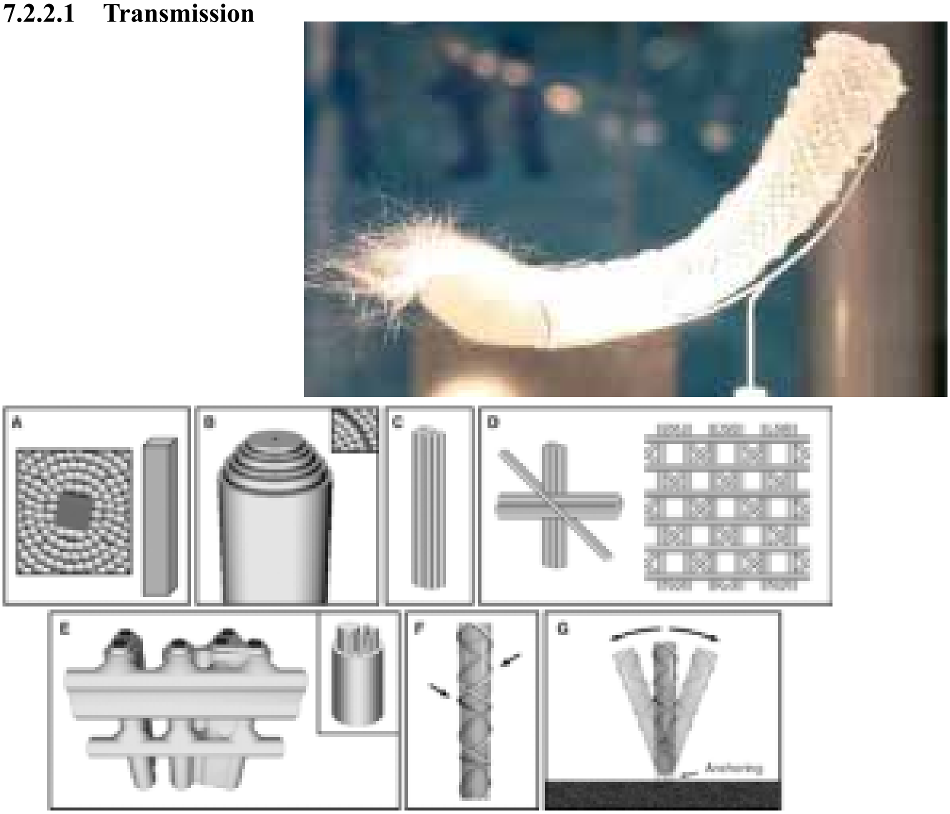


Figure 7.7 ....

Top: Venus flower basket sponge, courtesy of Cliff1066 [2008]. Bottom: "*Proposed scheme summarizing the seven levels of structural hierarchy in the skeletal system of Euplectella sp. (A) Consolidated silica nanoparticles deposited around a preformed organic axial filament (shown on the right). (B) Lamellar structure of spicule made of alternating organic and silica layers. Inset depicts the organically glued interlayer region. (C) Bundling of spicules. (D) (Right) Vertical and horizontal ordering of bundled spicules forming a square-lattice cylindrical cage with every second cell reinforced by diagonal elements (see Eq. 2). (Left) The node structure. (E) Cementation of nodes and spicules in the skeletal lattice with layered silica matrix. (Inset) Fiber-reinforced composite of an individual beam in the strut. (F) Surface ridges protect against ovalization of the skeleton tube. (G) Flexural anchoring of the rigid cage into the soft sediments of the sea floor*", reproduced from [Aizenberg *et al.* 2005], used with permission from The American Association for the Advancement of Science.

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The molecular structure of a substance influences the fraction of radiant energy passing through, which is described as transmittance [Merriam-Webster]. In dark environments, organisms need to adapt to the very limited radiation available, thus a high transmittance substances are advantageous. For example, the Venus flower-basket a deep-sea sponge (Figure 7.7), Euplectella, living up to 5000 meters deep has high transmittance characteristics [Aizenberg *et al.* 2004]. Its structural support is composed of a lattice of fused spicules that provide structural rigidity, generally 5-15 cm long and 40-70 μm in diameter [Perry & Keeling-Tucker 2000, Aizenberg *et al.* 2004]. Beyond the structural anchorage support characteristics of the Venus flower-basket, it has a remarkable effective fibre-optical network for light distribution in the deep-sea environment [Sundar *et al.* 2003]. The spicules of the Venus flower-basket are made of silica, which is the main ingredient of glass, but with better structural stability (Figure 7.7): "*The structural complexity of the glass skeleton in the sponge Euplectella sp. is an example of nature's ability to improve inherently poor building materials. The exceptional mechanical stability of the skeleton arises from the successive hierarchical assembly of the constituent glass from the nanometer to the macroscopic scale. The resultant structure might be regarded as a textbook example in mechanical engineering, because the seven hierarchical levels in the sponge skeleton represent major fundamental construction strategies*" [Aizenberg *et al.* 2005].

7.2.2.2 Refraction

Different geometries of eye structure affect the interception of light, and allow a focused or unfocused image. The large compound eyes allow the fly to respond quickly on the smallest movement in its neighbourhood with a 360 degrees vision, despite the unfocused perceived image [Moses 2006]. The compound eye consists of a large number of independent visual receptors, called facets or ommatidium (singular of ommatidia). The ommatidia are densely packed and arranged in a hexagonal array, see Figure 7.8. The ommatidium ensures the interception of light from one specific area, and prevents perceiving duplicated images from several ommatidia. In this case, the total image is the assembly of the information perceived from each independent ommatidia, just like the pixels of a digital monitor.

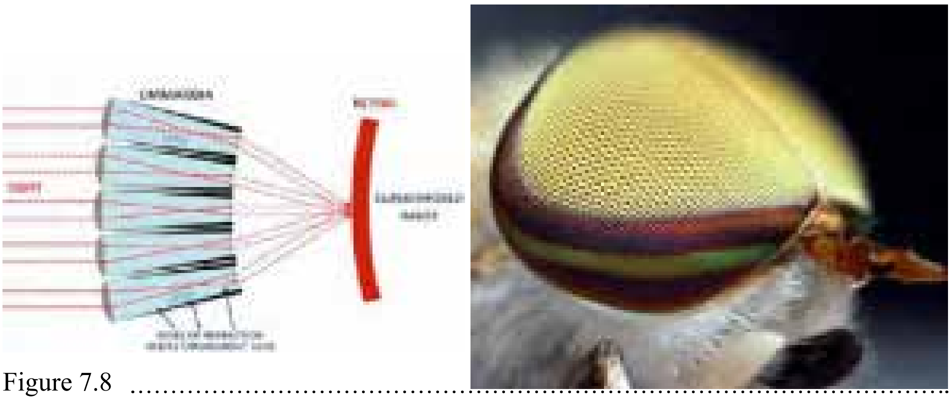

Figure 7.8

Left: Schematic drawing of the refraction superposition compound eye, reproduced from Watcher [2009], used with permission from Watching the world wake up. Right: the dense pack of facets of the fly eye – Photograph by © Thomas Shahan.

7.2.2.3 Reflection

Eyes of *decapod crustacea*[3] are different than those of flies, where image is formed by reflection rather than refraction [Land 1976], see Figure 7.9. These types of eyes are described as reflecting superposition compound eye [Land 1988]. The eye consists of densely arranged square facets on a spherical surface connected to square tubes (Figure 7.9). The inner surfaces of the square tubes are highly reflective. Specific geometrical alignments of the square tubes reflect the entering light and focus it on one focal point on the retina. The angle of the alignment is very crucial to reflect and focus numerous rays on one point [Land 1988]. Additionally, Land [1978] suggests the length of the tube to be twice the width to focus the reflections on the retina on one point. Compound eyes are either superposition or apposition, where "*superposition eyes are more sensitive than apposition eyes, which is why they are most commonly encountered in animals such as moths and fireflies that are active at night, or in marine crustaceans from the mid-water depths where the light regime is similar to moonlight on the surface*" [Land & Nilsson 2012].

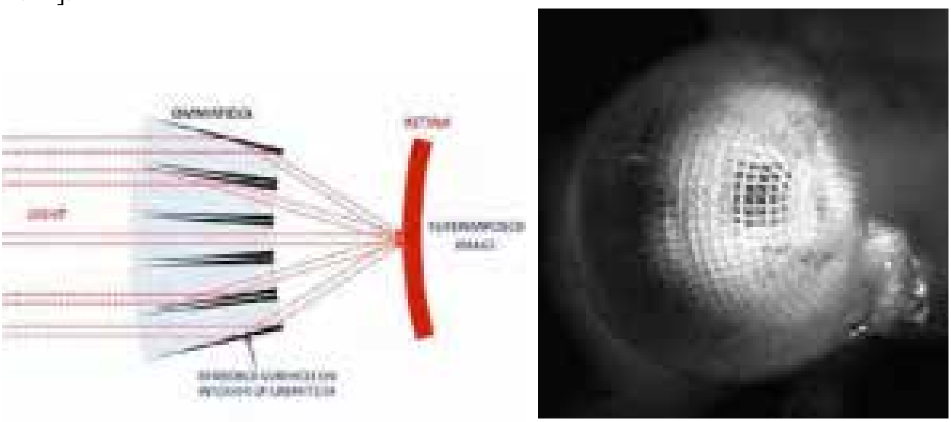

Figure 7.9 ....

Left: Schematic drawing of the reflection superposition compound eye, reproduced from Watcher [2009], used with permission from Watching the world wake up. Right: "*the reflecting superposition eye of the grass shrimp, Palaemonetes pugio. Note the square facets easily visible on the surface, which are nearly diagnostic of this optical design*", reproduced from [Cronin & Porter 2008], used with permission from Springer.

7.2.2.4 Absorption

In plants, and in other organisms, light can be absorbed by proteins, known as photosynthetic reaction centre, in order to perform photosynthesis. These proteins contain Chlorophyll (a green pigment), which is responsible for light absorption. The absorbed light is converted into chemical energy by using carbon dioxide and water, and releasing oxygen as a waste product.

3 Include shrimps, prawns, crayfish, and lobsters.

Absorbing radiation via dark colours is one of the ways to reduce reflections. For example, the meerkat has a black region of fur surrounding its eyes for a better vision at high radiation intensities in the desert (Figure 7.10). This black region absorbs radiation and prevents reflections, thus reduce glare that might interfere with his vision.

A class of fungi, known as radiotrophic fungi, absorbs high frequency electromagnetic rays (e.g., gamma-rays), which are biologically hazardous [Castelvecchi 2007]. Radiotrophic fungi use pigment melanin to convert the absorbed gamma-rays into chemical reaction used for its growth [Dadachova 2007].

Figure 7.10

Left: family of Meerkat near Oudtshoorn, South Africa. Courtesy of Mumpel2000 [2010]. Right: the black fur surrounding the eye. Courtesy of Olaf Leillinger [2005].

7.3 Exploration model for light regulation

The previous sections of this chapter defined the various entities of the exploration model, and discussed their interrelationships. The investigation and exploration of light regulation in nature is based on two initial functions: manage interception and manage intensity (see Figure 7.11). Each function incorporates different processes, where some are indicated in the exploration model for light regulation. The exploration model is classified based on four levels. On the first level the functional aspects are identified: manage interception and manage intensity. The second level of exploration distinguishes the processes that manipulate the identified functional aspects, e.g. exposure. The influential factors affecting the distinguished processes are explored on the third level, e.g. geometry. These factors lead to the fourth level of exploration, where pinnacles represent a particular function, e.g. succulent for light intensity management. The content of the presented model is a representative state for the current exploration, where it can be extended and new entities at the various levels may be added in future elaborations. The systematic representation of entities and their relationships support the access to relevant information, which is further discussed in the following section by an example. From the governed exemplary pinnacles, the exploration model shows that in order to manage light intensity the influential factors are found to be morphological.

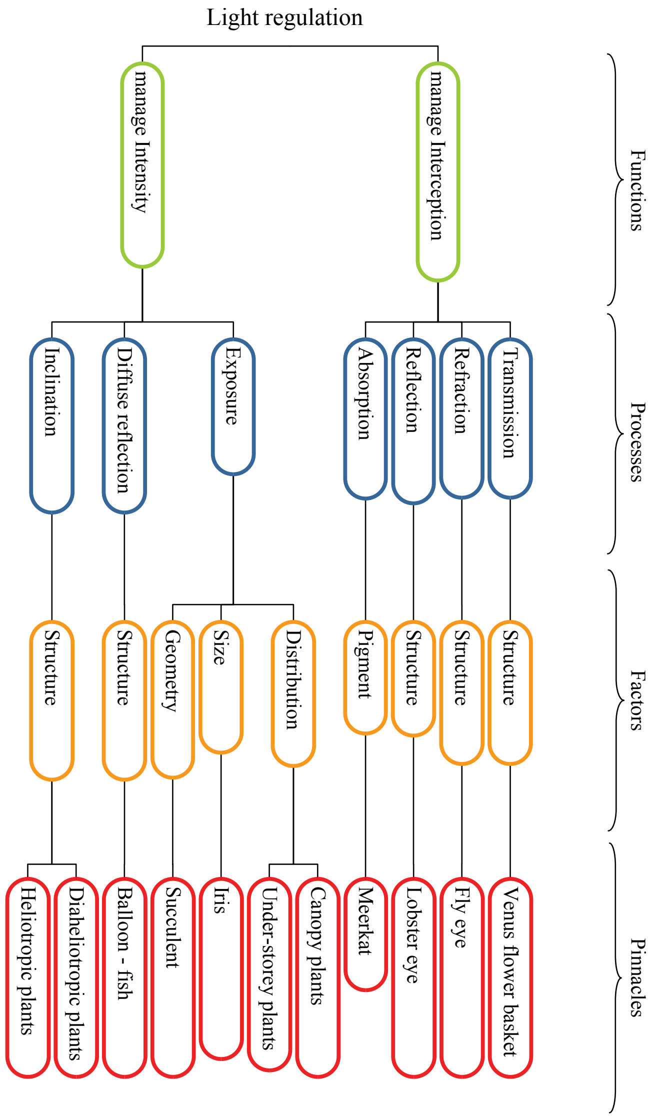

Figure 7.11 ....

Exploration model for light regulation.

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7.4 Example: shading system

The dynamic changes of solar radiation requires the building envelope to manage radiation regularly in order to minimize heat gain, maximize daylight, and prevent glare. The common way to manage radiation is through screening. Various strategies for radiation screening, related to orientation, are currently implemented in buildings (diffuse or direct) for the occupant comfort [Hausladen *et al.* 2008]. Standard shading systems have either vertical or horizontal louvers that control radiation variations by flipping to different angles (Figure 7.12). However, these louvers are not adapted, three-dimensionally, to track the exact sun radiation throughout the day. They tend to have the same angle of inclination when flipped (Figure 7.13). Venetian blinds, which consist of adjustable louvers, can be divided into separate parts, for controlling and adjusting them in different inclinations. This will control the sun radiation to get deeper in the room or reflecting it [Knaack *et al.* 2007]. But still, this divided configuration doesn't adjust in accordance to the changes of the azimuth angles.

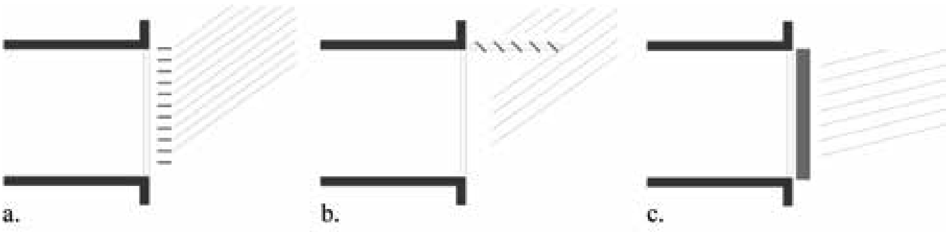


Figure 7.12

Simplified version of current shading devices. (a & b) horizontal shade devices for high angles of radiation. (c) Vertical shade devices for low angles of radiation (morning and evening).

Figure 7.13

All shade blades have the same angle of inclination α when flipped. Light and dark grey indicate the old and new positions, respectively.

7.4.1 **Definition of the design challenges** (step 1)

The challenge defined for this example is to design a shading system that adapts to light intensity via geometry arrangements to prevent direct radiation throughout the day.

7.4.2 **Identification of exemplary pinnacles** (step 2)

"Shading system" is relevant to the function regulate intensity. "Adapts to light intensity via geometry arrangements" implies the processes exposure and inclination and the factors distribution, geometry and structure, as presented in Figure 7.14. Among the relevant pinnacles the selected ones (i.e. canopy plants, under-storey plants, succulent, diaheliotropic plants) are summarized in the next section – this step is based on the third step filtering (see chapter 3).

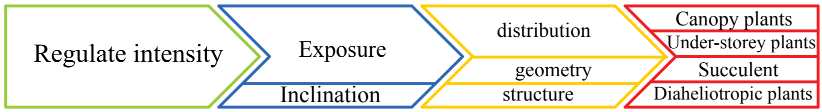


Figure 7.14

The extracted exploration path.

7.4.3 **Analyses of the selected pinnacles** (step 3)

The current section investigates the selected pinnacles for regulating light intensity. The following pinnacles: canopy plants, under-storey plants, diaheliotropic plants, and succulents, are analyzed and summarized in section 7.4.3.1.

Pinnacle 7.1 Canopy plants

Regulation of leaf inclination is one of the mechanisms for avoiding shading by neighbours [Mullen *et al.* 2006]. Leaves with flatter and smaller angle inclination are found in forested sites with lower light levels [Muraoka *et al.* 1998]. Inclinations at lower canopy leaves are lower than at upper canopy leaves [Barradas *et al.* 1999], Figure 7.15. Leaflet folding to reduce radiation exposure is noticed only at the deforested site where light levels are high, because increasing the slope of leaflet surfaces reduces the photosynthesis saturation level [Muraoka *et al.* 1998].

When new leaves are developing, causing self-shading, the lower leaves, which are getting shaded by the new ones, rotate in the horizontal plane to minimize the shade caused by the new leaves [Pearcy *et al.* 2005]. Reorientations are caused by inclination of leaves and by differential growth in the expanding leaves, especially at the petiole, resulting in leaf curvature [Mullen *et al.* 2006]. Schematic representations of leaf inclination for shade avoidance are presented in Figure 7.16.

Figure 7.15

Multilayer and loose distribution of leaves at forested sites.

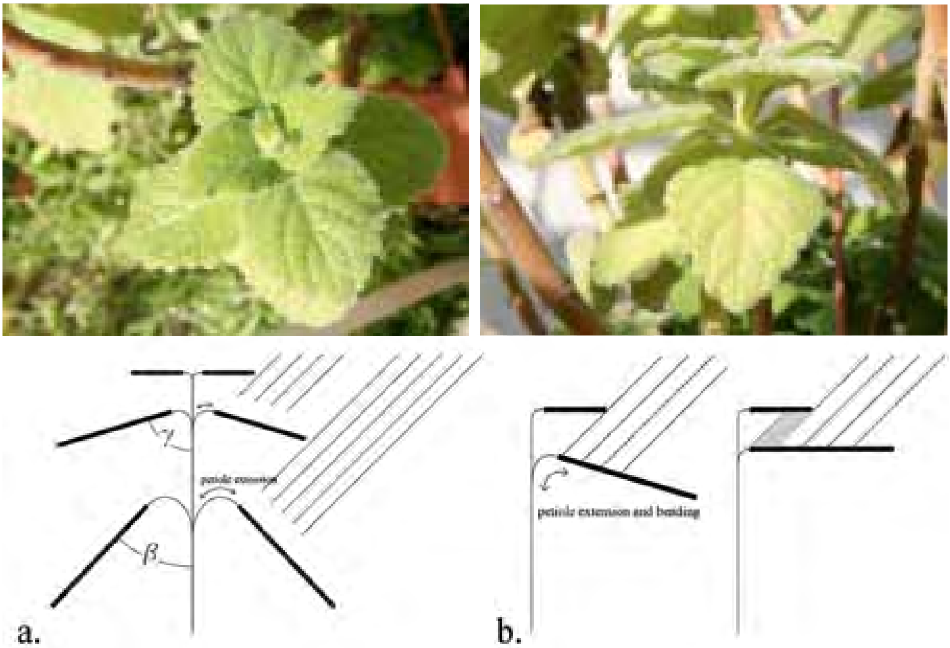


Figure 7.16

Lower layers of leaves bend for maximum light interception. (a) Lower leaves get bigger with smaller inclination ($\beta < \gamma$). Alternation of 90 degrees is adopted in this plant for more space between the layers in order to catch more sun light. (b) The effect of the inclination, preventing self shading.

Pinnacle 7.2 Under-storey plants

Leaf distribution for photosynthesis efficiency is achieved by a monolayer with high density or multi-layer with loosely distribution [Horn 1971]. Leaf density of plants, influences plant's projected area, which leads to the relation between plants' projected area and sunlight interception capability [Niklas 1988]. In shaded environments, species tend to have taller stems in order to overtop neighbouring plants [Poorter & Werger 1999], whereas under-storey species tend to expand horizontally investing in the growth of their leaves for increased light interception [King 1991]. By expanding horizontally they maximize their planar area for maximum exposure of diffused light, see Figure 7.17.

Figure 7.17

Monolayer and dense distribution of leaves at under-storey plants.

Pinnacle 7.3 Ribbed Cacti

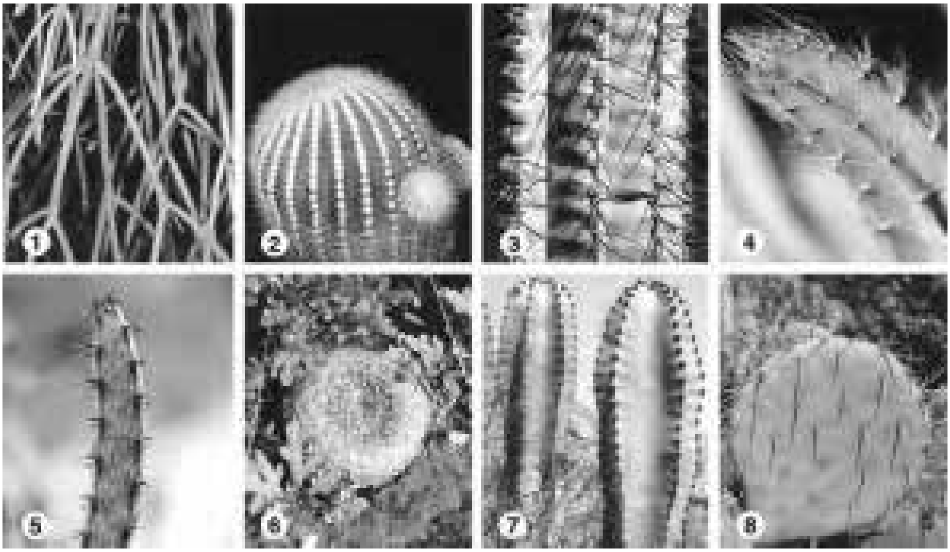
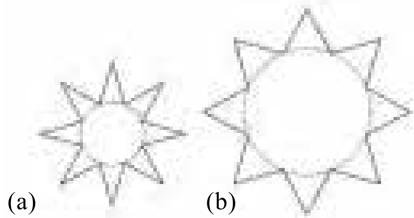


Figure 7.18

(1-8) Succulent with increased surface area-volume ratio due to the pleated morphology. (a-b) the ribbed morphology allows swelling and shrinking. Images adapted from [Mauseth 1999], ordered from American journal of botany.



Some succulents are characterised by their ribbing morphology (Figure 7.18, 1-8), where "*the main physiological function of ribs may be to allow swelling of the cactus stems and hence storage of water following rainfall*" [Nobel 1980], see Figure 7.18 a-b. Furthermore, the ribbed morphology might generate turbulent flow with thinner boundary layer next to the surface, thus contributing in cooling [Nobel 1988, Mauseth 2000]. In terms of light, the ribbing morphology, despite the increased surface-area to volume ratio, creates situations of self-shading, thus reducing transpiration rates [Nobel 1980, Mauseth 2000]. The geometrical variations in cacti are considered as a result of adaptations to photosynthetically active radiation interception [Nobel 1980].

Pinnacle 7.4 Diaheliotropic plants

In plants, sun tracking is achieved in two ways: move leaves perpendicular to the direct sun rays, which are called diaheliotropic leaves, and move leaves parallel to direct sun rays, are called paraheliotropic [Ehleringer & Forseth 1980]. Heat load, leaf temperature and transpiration rate are reduced at paraheliotropic movements [Forseth & Ehleringer 1980]. Diaheliotropic movements allow a high solar irradiation and result in maximal rates of photosynthesis throughout the day [Mooney & Ehleringer 1978]. The interpretation of the influence of angle of incidence on solar irradiance is presented in Figure 7.19.

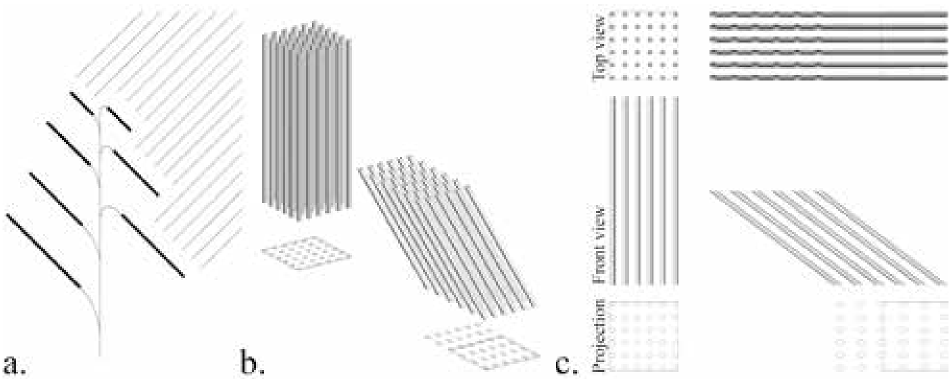


Figure 7.19

The angle of incidence determines energy density. (a) Leaves normal to sun radiation for maximum energy gain. (b) The effect of different inclination on the projection. (c) Top, front, and projection view.

7.4.3.1 Pinnacle analysing

Increased exposure at canopy, under-storey, and diaheliotropic plants, and decreased exposure in succulents, are analyzed and summarized in Table 7.1. The brief description of the strategies applied by the pinnacles and their abstraction to mechanisms, main principles, and main features, provide a functional guideline for the design process.

Summary of pinnacles analyses.

Table 7.1

Pinnacle's Strategy	Mechanism	Main principles	Main feature
Canopy plants Increase radiation exposure by multilayer arrangement of leaves with loose distribution	Small leaves (rather than big) distributed at various levels to allow the solar radiation to penetrate through and get to the depth. Stem and petiole elongation cause varied leaf inclinations and curvatures along the plant. The newer the leaf the higher the inclination (horizontal).	Petiole elongation and varied inclinations of leaves at different heights	Elongation Inclination
Under-storey plants Increase radiation exposure by monolayer arrangement of leaves with dense distribution	Plants expand horizontally with dense distribution of leaves, where they maximize their projected area	Monolayer layer and dense distribution of leaves	Maximized projected area
Diaheliotropic Plants Maintain surfaces perpendicular to radiation for maximized exposure	Photoreceptor cells respond to radiation and shrink or swell for bending and keep an inclination of leaves normal to radiation	Normal to sunrays for maximum exposure	Tracking
Succulent Reduce exposure by reduced projected area for radiation	Pleated body morphology with surfaces almost parallel to radiation prevent excess heat loads	Surface orientation avoiding normal to radiation	Pleated

7.4.4 **Design path matrix** (step 4)

The analyses matrix of the selected pinnacles for light intensity regulation is presented in Table 7.2. For light intensity regulation, morphological adaptations are dominating to affect performance of the exposure management. The relevant categories for radiation regulation have a strong relevance to morphology, where configuration and dynamics were observed to play a major role in these selected pinnacles. The selected pinnacles belong to plants and have direct relation to radiation due to their need for photosynthesis.

The superposition of exposure and inclination to regulate light intensity is presented in the design path matrix, Figure 7.20. The dominant features of: dynamic configuration, morphological adaptation, and meso scale, are determined. Dense and monolayer features are distinguished for the morphological features. Furthermore, the dynamics for light intensity regulation are generated through elongations, inclinations, and rotations. As a result, the design path matrix yielded in a set of features and some physical relationships for the design concept generation, which is presented in the next step.

Table 7.2 Pinnacle analysing matrix.

Challenge	Pinnacles	Processes: Exposure	Processes: Inclination	Configuration: Dynamic	Configuration: Static	Adaptation: Physiological	Adaptation: Morphological	Adaptation: Behavioural	Scale: Nano	Scale: Micro	Scale: Meso	Scale: Macro	Environmental context: Arid	Environmental context: Tropical	Environmental context: Moderate	Environmental context: Continental	Environmental context: Polar	Environmental context: Aquatic	Morphological features: Dense	Morphological features: Loose	Morphological features: Monolayer	Morphological features: Multilayer	Morphological features: Pleated	Dynamics: Elongation	Dynamics: Inclination	Dynamics: Rotation	Dynamics: Projection	Dynamics: Horizontal expansion
ılate intensity																												
	Canopy plants	X		X			X				X		X	X	X	X				X		X		X	X	X		
	Under-storey plants	X		X			X				X			X	X	X			X		X						X	X
	Succulent	X		X			X				X		X										X				X	
Exposure		X		X			X				X		X	X	X	X			X	X	X	X	X				X	
	Diaheliotropic plants		X	X			X				X				X	X			X		X			X	X	X		
Inclination			X	X			X				X				X	X			X		X			X	X	X		

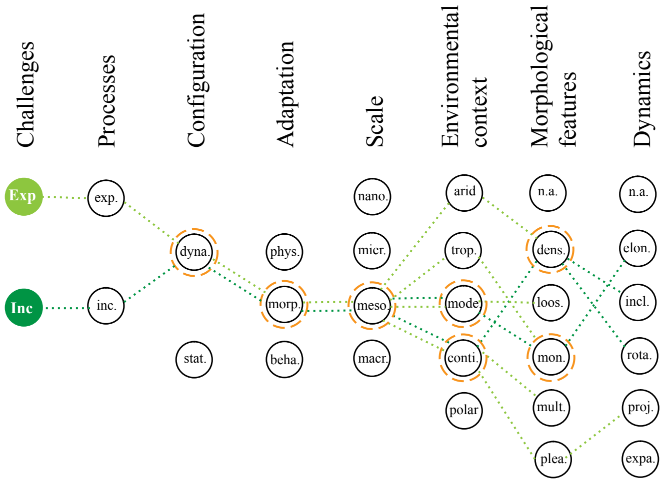


Figure 7.20 Design path matrix. Each vertical column represents a category and its various features. Light green lines denote the path of exposure, the dark green denote the path of inclination, and the orange nodes denote the dominant features which represent the design path.

7.4.5 **Preliminary design concept proposal** (step 5)

The azimuth and altitude angles of sun, throughout the days of the year, are considered for the design concept generation (Figure 7.21). The pleated morphology is translated into the concept of numerous sheets at monolayer distribution at different depths to radiation, where the system blocks the sun radiation at a specific angle and allows the indirect light to penetrate between the sheets (Figure 7.22). In this case, indirect light reflected from the surrounding environment reaches behind the system and keeps the interior space with good quality of light. Additionally, shading sheets being perpendicular to sun rays is the preferred orientation for radiation gaining, where photovoltaic cells are attached to the surface facing radiation.

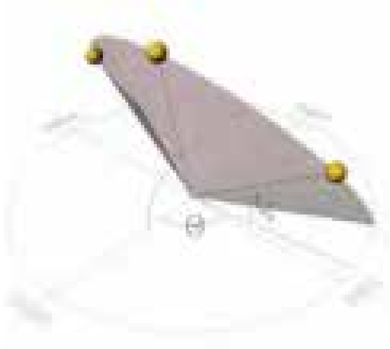


Figure 7.21

Sun position and path. Altitude and azimuth angles determine the position of sun. The altitude angle (ω) is the angle of sun above the horizon and the azimuth (θ) is the angle of sun's projection on the ground plane relative to south. The hatched surface represents sun's radiation path throughout a specific day.

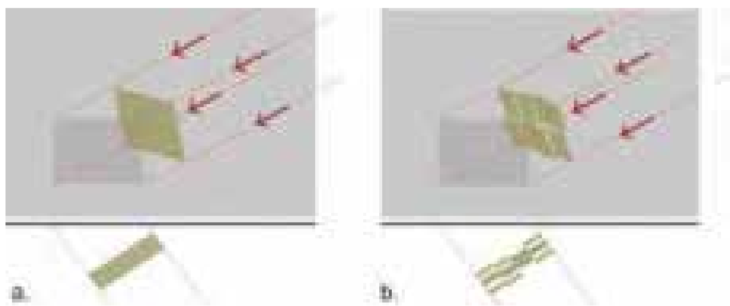


Figure 7.22

The same projection area for two different surfaces of shading sheets perpendicular to radiation rays. (a) the shading sheet flat and normal to sun rays. (b) the shading sheet is divided into smaller pieces and positioned normal to radiation at different depths.

The design concept aims in adjustability to track solar radiation path throughout the day. Additionally, a potential integration of energy generating elements on the shading sheets facing radiation may improve performance in terms of energy. The design concept solution consists of shading sheets, tubular members and profiles, Figure 7.23. The shading sheets are connected to the tubular supporting members via an elastic membrane for flexibility. The profiles create a grid, which allows the tubular members to roll over and control their position according to shading requirements. For sun radiation blocking, the shading sheets are flexible and can be adjusted to different inclinations.

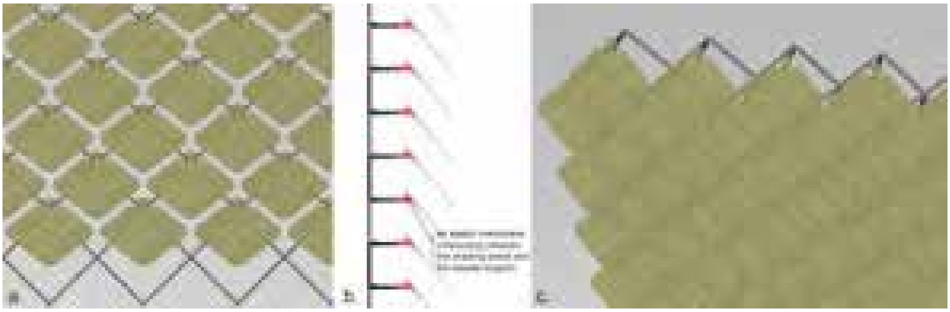


Figure 7.23

The shading system. (a) front view, shading sheets and profiles in the back. (b) side view, shading sheets connected to the tubular member via the elastic membrane. (c) perspective view.

7.4.5.1 The shading component

The shading component consists of a sheet attached to a supporting tubular member with the property of elongation (Figure 7.24). This elongation is important to avoid shading by neighbours. The sheet is able to have different inclinations (Figure 7.24, a-c), where it covers and blocks the sun radiation path, which is determined by azimuth and altitude angles, throughout a day.

The shading component is connected to the grid of profiles allowing the components to move and change position according to users shading requirements. Four elastic wires are attached to each sheet at their corners, when one of the wires is stretched the sheet will rotate and change its inclination. The specific required inclination for a sheet is controlled via these four wires (Figure 7.25). The components are controlled separately with considering each other's position and inclination in order to have the maximum variation of shading patterns.

The system could be applied on a flat envelope or on a freeform envelope. The scale and size of the gird depends on the specific envelope to be applied on. In cases where the envelope has a freeform layout, the grid has smaller dimensions than at a flat envelope.

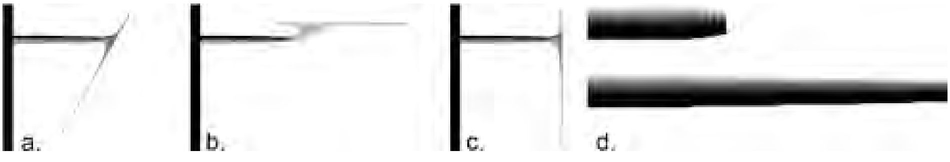


Figure 7.24

The shading sheets inclination and their support elongation. (a.-c.) showing different inclinations of the sheet connected to the support member by an elastic membrane. (d) the support tubular member elongation.

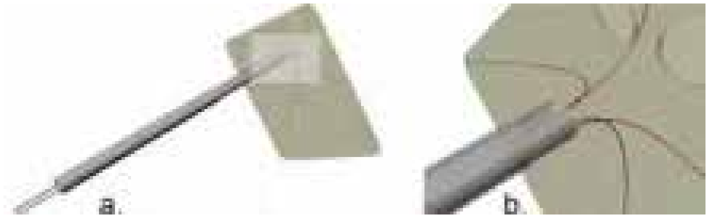


Figure 7.25

The shading component. (a) four strings attached on the sheet, reaching the corners and inserted into the tubular member. (b) a close-up to the four strings interring the tubular member.

7.4.6 Evaluation of performance

The main aim of the simulations is to check the configuration of the shading system to track sun radiation throughout a day. These simulations refer to a specific location which is Delft at 52°0′54″N 4°21′24″E (Figure 7.26), with considering three critical days throughout the year, where noon hour was determined (Table 7.3). The tested side of the envelope is south with 90° inclination.

Figure 7.26

The shading system location, inclination and orientation.

In this evaluation, the size of grid and amount of elements does not affect the way the shade is generated on the envelope. The dynamic projection of shading sheets, caused by sun radiation, on the envelope was studied. The values in Table 7.3 and 7.4 are generated from an online calculator for sun angles [Gronbeck 1998]. The path of sun radiation is determined by altitude and azimuth angles. These angles change throughout the day and differ from day to day. The evaluation refers to morning and noon azimuth and altitude angles, since noon and afternoon need the same treatment but mirrored because of their similarity in relation to south (Table 7.4).

Sun radiation period through three critical days throughout the year in Delft (day almost equal to night, shortest day and longest day).

Table 7.3

Reference Date	**Sun duration** (hours)	**Sunrise**	**Sunset**	**Noon**
September 21	12:20	06:27	18:47	12:37
December 21	7:45	08:49	16:34	12:42
June 21	16:44	04:23	21:07	12:45

Table 7.4 Morning, noon and afternoon altitude and azimuth angles for three days

	September 21			December 21			June 21		
Time	08:00	12:37	17:00	10:00	12:42	15:00	09:00	12:45	18:00
Altitude	13.16°	38.66°	15.13°	6.67°	14.56°	8.75°	38.74°	61.44°	34.40°
Azimuth	73.86°	0.03°	-70.80°	36.86°	0.01°	-31.71°	78.54°	0.36°	-84.64°

For the simulations, a system that has an initial status as in Figure 7.23c was considered. It consists of 67 shading sheets distributed as a single layer all over the grid. The aim was to shade the grid with minimum shading sheets and prevent situations where two sheets shade the same spot (self-shading) in order to maximize exposure (e.g., for using solar cells), thus increase solar gain of the solar cells positioned on the top of each sheet. In the results (Figure 7.27) where sheets less than 67 are shown, means that the other sheets are not required for shading generation. Two simulations were carried out for each of the selected days, one at morning and one at noon.

Day 1 (Figure 7.27a): on June 21st, sun rays have high altitude angle at noon, which resulted in shading the surface with few shading sheets normal to sun rays (Figure 7.27a left). In this case the sheets have the same inclination, but the rows of shading sheets are not at the same distance from the shaded surface; this is important in order to avoid shading by neighbours. In the morning (Figure 7.27a right), when sun radiation reaches the southern facade then it will have already moderate altitude angle but with high azimuth, and resulted in shading with different organization and less sheets but with more surface area of shade.

Day 2 (Figure 7.27b): on September 21st sun rays have moderate altitude angle at noon, which needed more shading sheets to provide the required protection (Figure 7.27b left). In this case the sheets have the same inclination, but sheet rows are not at the same distance from the envelope, in order to avoid self-shading. In the morning, sun rays have high azimuth and low altitude which results in shading sheets concentration at east with relatively dense distribution (Figure 7.27b right).

Day 3 (Figure 7.27c): on December 21st sun rays have low altitude angle at noon, where more dense distribution was needed to provide the required shading (Figure 7.27c left). In this case the sheets have the same inclination with different distances from the envelope, this was a way to provide a stronger visual contact with outside and lighten the perceived density of the shading system by creating the openings and division (the same principle as in Figure 7.27b). In the morning, sun rays have low altitude and moderate azimuth angles which resulted in having a large number of sheets, in order cover the required surface of the envelope, with high density (Figure 7.27c right). The same principle of distribution at noon was applied in the morning, where sheets have different distances from the envelope.

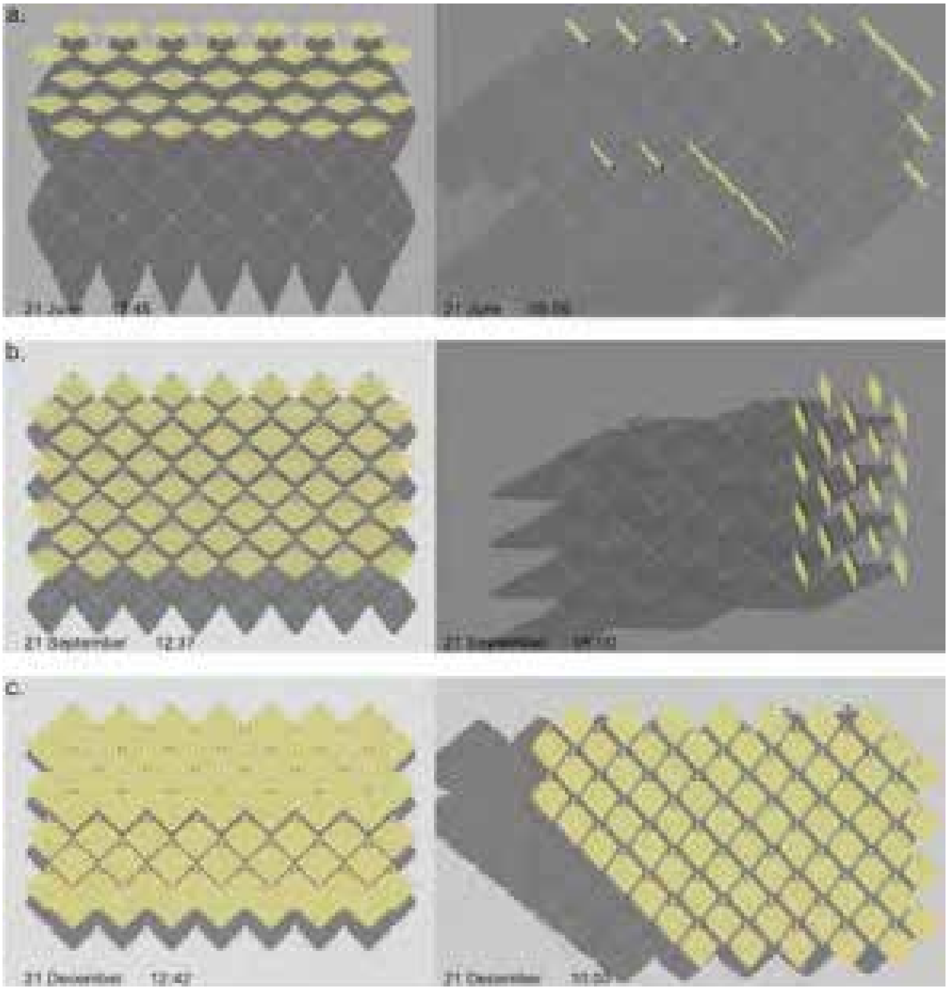


Figure 7.27

Shading results for the system located in Delft and facing south. (a) on the 21st of June at noon (left) and at morning (right). (b) on the 21st of September at noon (left) and at morning (right).

7.5 Conclusions

Current standard shading systems, such as louvre panels either vertical or horizontal inclinations, have a limited adjustability to screen the dynamic sun radiation. They flip around one axis, which does not cover the radiation path throughout a day. The limited adjustability is due to their design principle, where louvres have their best performance at noon at a specific azimuth (designed for the most critical situation). This poor consideration results in cases where louvres are totally closed in order to block varied sun radiation, e.g. low altitude and high azimuth angles of radiations.

Organisms in nature have developed special strategies and mechanisms to cope with the different light intensities in their environments. They can regulate various exposures and avoid discomfort by manipulating the properties of the light interception medium, e.g. Balloon-fish eye. Plants determine the amount of exposure for the efficient performance by several strategies. For example, plants have special organisational features for sun tracking, self-shade avoiding, efficient packing, and relatively high plasticity in the plant's body. At minimum exposure, plants are less dynamic and reorient when having high exposure, e.g. at noon, also they tend to have low leaf inclinations, preventing conditions such as normal to rays. Physiological and morphological adaptations are significant factors influencing light interception in plants. Abstracting the main principles from plants and transforming them into technical solutions for buildings, is a promising development.

The living envelope strategy was applied in the concept generation of the adaptive shading system. First, strategies for light intensity regulation in nature were investigated. Second, the biological information was presented in the radiation exploration model, which emphasized the relationship between the various aspects of functions, processes, factors, and pinnacles. Third, the selected pinnacles were analysed and applied in the design path matrix, which resulted in the path of the dominant features to be addressed in the design concept generation. This strategy resulted in the abstraction of principles to realize the potential transformation into a design concept of the adaptive shading system.

The concept of the adaptive shading system is based on principles and methods abstracted from the special organisational features of plants. The proposed system has a configuration that is able to track sun radiation and provide shade for the desired plane of the envelope. It has flexible shading sheets that can rotate around their support. These supports are tubular members that can elongate and position the shading sheets in different distances from the envelope. The shading system is designed for the whole range of solar radiation throughout a day during the year, where azimuth and altitude angles that determine radiation path were taken into consideration. The shading system is able to avoid self shading situation by elongating their support tubular members and by that they have different distances from the envelope, like leaves in plants elongate their petioles. If we compare it with existing shading systems, then we realize that current shading systems consider altitude angles or azimuth angles but not their combined influence (horizontal louvres for high altitude angles or vertical louvres for low altitudes in the morning or evening). This combination of altitude and azimuth is very important in order to cover the path radiation throughout the day, which is achieved in the designed system above. From the simulations, it was noticed that altitude angles, at envelopes facing south, affect significantly the density of shading sheets distribution. For low altitudes in the morning, sheets are more concentrated to the eastern side of the envelope with high or low density, depending on the azimuth angle. For different combinations of altitude and azimuth angles, different organisational patterns of the shading system are generated.

Due to the configuration of the system that allows it to orient to different directions and reposition through the day, it is able to provide continuous shading all over the desired plane at the envelope in Delft. With the system it is possible to achieve maximum required shaded area with loose density of shade planes and avoiding self-shading, or shading with high density of shade planes for maximum energy gaining, due to their position normal to sun rays. Further investigation on the flexibility possibilities of the sheets is needed in order to adapt the system to different locations with different altitude and azimuth angles. Furthermore, some improvements could be considered, in the case of very high altitude angles where the system has difficulties shading the upper parts. A proper solution could be, allowing the sheets to fold and have better contact with the envelope (Figure 7.28); in this case, the sheets might have different inclination angles, increasing at higher positions.

The proposed shading system is a possible design concept outcome, whereas other concepts may be obtained by choosing various paths through the exploration model and analysing different pinnacles. The exploration model presents the current state of the investigation of radiation management strategies in nature, where a potential extension is possible by following the same rules.

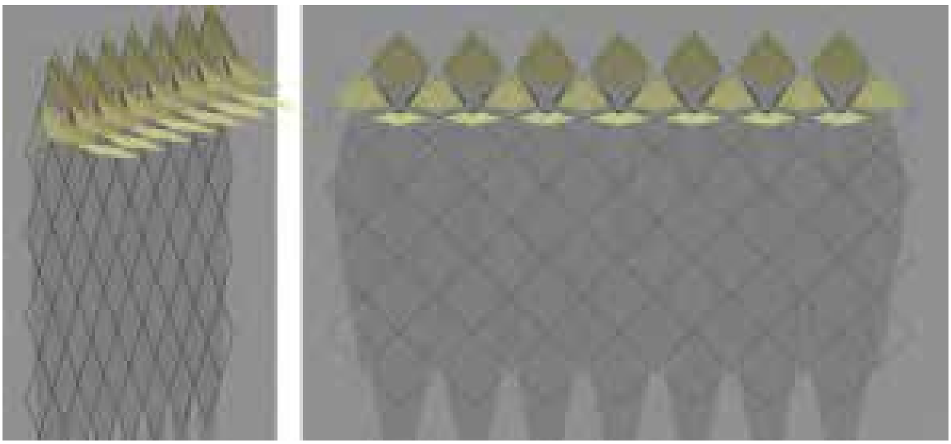


Figure 7.28

High altitude angles at noon. The shading sheets fold in order to provide more protection at the upper part.

References

Aizenberg, J., Sundar, V. C., Yablon, A. D., Weaver, J. C., & Chen, G. [2004] Biological glass fibers: Correlation between optical and structural properties. *Proceedings of the National Academy of Sciences of the United States of America*, **101**, 3358-3363.

Aizenberg, J., Weaver, J. C., Thanawala, M. S., Sundar, V. C., Morse, D. E., & Fratzl, P. [2005]. Skeleton of Euplectella sp.: Structural Hierarchy from the Nanoscale to the Macroscale. *Science*, **309**, 275-278.

Appleby, S.J. & Muntz, W.R.A. [1979]. Occlusable Yellow Corneas in Tetraodontidae. *The Journal of Experimental Biology*, **83**, 249-259.

Bar-Cohen, Y., (Ed.), [2006]. *Biomimetics: Biologically Inspired Technologies*, Boca Raton: CRC Press.

Barradas, V.L., Jones, H.G., & Clark, J.A. [1999]. Leaf orientation and distribution in a Phaseolus vulgaris L. crop and their relation to light microclimate. *International Journal of Biometeorology*, **43**(2), pp. 64-70.

Brunig, E.F. [1976], Tree forms in relation to environmental conditions: an ecological viewpoint. *Tree Physiology and Yield Improvement*, M.G.R. Cannell & F.T. Last (Eds.), London: Academic Press, pp. 139–156.

Castelvecchi, D. [2007]. Quantum capture: Photosynthesis tries many paths at once. *Science News*, **171**, pp. 229.

Cliff1066 [2008]. *Venus' Flower-basket Sponge (Euplectella speciosa)*, available online at: http://www.flickr.com/photos/nostri-imago/2951015978/ (retrieved August 2012).

Collins, S.P. and Collin, H.B. [2001]. The fish cornea: Adaptations for different aquatic environments. In: *Sensory Biology of Jawed Fishes: New Insights* (Kapoor, B.G., and Hara, T.J., eds.), pp. 57-96. Playmouth, UK: Science Publishers.

Compagno, A. [2002]. *Intelligent Glass Facades: Materials, Practice, Design* (5th ed.), Berlin: Birkhauser.

Darwin, C. [1880]. *The Power of Movement in Plants*, London: Murray.

Dadachova, E., Bryan, R.A., Huang, X., Moadel, T., and Schweitzer, A.D. [2007]. Ionizing Radiation Changes the Electronic Properties of Melanin and Enhances the Growth of Melanized Fungi, *PLoS ONE*, **2**(5), e457, doi:10.1371/journal.pone.0000457.

Ehleringer, J.R. & Forseth, I. [1980]. Solar Tracking by Plants. *Science*, **210**(4474), pp. 1094-1098.

Ezcurra, E., Montana, C., & Arizaga, S. [1991]. Architecture, light interception, and distribution of Larrea species in the Monte Desert. Argentina. *Ecology*, **72**(1), pp. 23-34.

Falster, D.S. & Westoby, M. [2003]. Leaf size and angle vary widely across species: what consequences for light interception?. *New Phytologist*, **158**(3), pp. 509-525.

Forseth, I. & Ehleringer, J.R. [1980], Solar tracking response to drought in a desert annual. *Oecologia*, **44**(2), pp. 159-163.

Gronbeck, C. [1998]. *SunAngle calculator*, available at online: http://www.susdesign.com/sunangle/ (retrieved March 2008).

Hader, D.P. & Lebert, M. eds. [2001]. *Photomovement*, Amsterdam: Elsevier Science B.V.

Hausladen, G., Saldanha, M., & Liedl, P. [2008]. *ClimateSkin: Building-skin Concepts that Can Do More with Less Energy*, Berlin: Birkhauser.

Hooker, W. [1865]. *A First Book in Physiology: For the Use of Schools and Families*, New York: Sheldon and Company.

Horn, H.S. [1971]. *Adaptive Geometry of Trees*, London: Princeton University Press.

Kevin Bryant [2010]. *IMG_4637acrre*, available online at: http://www.flickr.com/photos/mentalblock/5253913307/ (retrieved August 2012).

King, D.A. [1991]. Correlations between biomass allocation, relative growth rate and light environment in tropical forest saplings. *Functional Ecology*, **5**, pp. 485-492.

King, D.A. [1997]. The Functional Significance of Leaf Angle in Eucalyptus. *Australian Journal of Botany*, **45**(4), pp. 619-639.

Kiyosawa, K. & Tanaka, H. [1976]. Change in potassium distribution in a Phaseolus pulvinus during circadian movement of the leaf. *Plant & Cell Physiol.*, **17**, pp. 289-298.

Knaack, U., Tillmann, K., Bilow, M., & Auer, T. [2007]. *Facades: Principles of Construction*. Basel: Birkhauser, pp. 80-82.

Kriegh, M. & Kriegh, J. [2003]. Growth, Form and Proportion in Nature: Lessons for Human Habitation in off Planet Environments. *Proc. of the 33rd Int. Conf. On Environmental Systems (ICES)*, Vancouver, British Columbia, Canada. Pennsylvania: Warrendale, USA.

Land, M.F. [1978]. Animal eyes with mirror optics. *Scientific American*, **239**(6), pp. 88–99.

Land, M.F. [1988]. The optics of animal eyes, *Contemporary Physics*, **29**(5), 435-455.

Land, M.F. [2005]. The optical structures of animal eyes. *Current Biology*, **15**(9), pp. R319–R323.

Land, M.F. & Nilsson D.E. [2012]. *Animal eyes*,New York: Oxford University Press.

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., and Knippers, J., [2011]. Flectofin: a nature based hinge-less flapping mechanism. *Bioinspiration & Biomimetics*, **6**, special issue on Biomimetics of Movement, 045001.

Loomis, R.S., Williams, W.A., & Hall, A.E. [1971]. Agricultural productivity. *Annual Review of Plant Physiology*, **22**, pp. 431–468.

Matthews, L.A. & Giurgiutiu, V. [2006]. Modeling actuation forces and strains in nastic structures. In *Smart structures and materials 2006: smart structures and integrated systems*, Y. Matsuzaki ed., Proceedings SPIE 6173, O1-O10.

Mauseth, J.D. [2000]. Theoretical aspects of surface-to-volume ratios and water-storage capacities of succulent shoots. *American Journal of Botany*, **87**(8), pp. 1107-1115.

Merriam-Webster, an encyclopaedia, Britannica Company. Available from: <http://www.merriam-webster.com/dictionary/transmittance?show=0&t=1348376586>. (retrieved July 2012)

Mooney, H.A. & Ehleringer, J.R. [1978]. The carbon gain benefits of solar tracking in a desert annual. *Plant, Cell Environment*, **1**(4), pp. 307-311.

Moses, K. [2006]. Fly eyes get the whole picture. *Nature*, **443**, pp. 638-639.

Mullen, J.L., Weinig, C., & Hangarter, R.P. [2006]. Shade avoidance and the regulation of leaf inclination in Arabidopsis. *Plant, Cell & Environment*, **29**(6), pp. 1099-1106.

Mumpel2000 [2010]. *Family of Meerkat near Oudtshoorn, South Africa*, available online at: http://commons.wikimedia.org/wiki/File:Oudtshoorn_Meerkat.jpg (retrieved August 2012).

Muraoka, H., Takenaka, A., Tang, Y., Koizumi, H., & Washitani, I. [1998]. Flexible Leaf Orientations of Arisaema heterophyllum Maximize Light Capture in a Forest Understorey and Avoid Excess Irradiance at a Deforested Site. *Annals of Botany*, **82**(3), pp. 297-307.

Nhobgood Nick Hobgood [2008]. *Diodon holocanthus (Balloonfish)*, available online at: http://commons.wikimedia.org/wiki/File:Diodon_holocanthus_(Ballonfish).jpg (retrieved August 2012).

Niklas, K.J. [1988]. The Role of Phyllotatic Pattern as a “Developmental Constraint” On the Interception of Light by Leaf Surfaces. *Evolution*, **42**(1), pp. 1-16.

Nobel, P.S. [1980]. Interception of Photosynthetically Active Radiation by Cacti of Different Morphology. *Oecologia* (Berl.), **45**, pp. 160-166.

Olaf Leillinger [2005]. *Meerkat (Suricata suricatta)*, available online at: http://commons.wikimedia.org/wiki/File:Suricata.suricatta.6860.jpg (retrieved August 2012).

Orlov O.Y. & Gamburtzeva A.G. [1976], Changeable coloration of cornea in the fish Hexagrammos octogrammus. *Nature*, **263**, pp. 405-406.

Orlov, O.Y. & Kondrashev, S.L. [1998]. Changeable coloration of cornea in fishes and its distribution. *Iugoslav Physiol Pharmacol Acta*, **34**, pp. 359–369.

Parkin, I. P., & Manning, T. D. [2006]. Intelligent Thermochromic Windows. *Journal of Chemical Education*, **83**(3), pp. 393.

Pearcy, R.W., Muraoka, H., & Valladares, F. [2005]. Crown architecture in sun and shade environments: assessing function and trade-offs with a three-dimensional simulation model. *New Physiologist*, **166**(3), pp. 791-800.

Perry, C. C. & Keeling-Tucker, T. J. [2000]. Biosilicification: the role of the organic matrix in structure control. *Journal of Biological Inorganic Chemistry*, **5**, pp. 537–550.

Poorter, L. & Werger, M.J.A. [1999]. Light environment, sapling architecture, and leaf display in six rain forest tree species. *American Journal of Botany*, **86**(10), pp. 1464-1473.

Presti, D. & Delbruck, M. [1978]. Photoreceptors for biosynthesis, energy storage and vision. *Plant, Cell & Environment*, **1**, pp. 81–100.

Saeli, M., Piccirillo, C., Parkin, I.P., Binions, R., and Ridley, I. [2010]. Optimisation of Thermochromic Thin Films on Glass; Design of Intelligent Windows. *Advances in Science and Technology*, **75**, pp. 79-90.

Satter, R.L. [1979]. Leaf movements and tendril curling. *Physiology of Movements, Encyclopedia of Plant Physiology (new series)*, 7, W. Haupt & M.E. Feinleib (Eds.). New York: Springer-Verlag, pp. 442–484.

Shell, G.S.G., Lang, A.R.G., and Sale, P.J.M. [1974]. Quantitative measures of leaf orientation and heliotropic response in sunflower, bean, pepper, and cucumber. *Agricultural Meteorology*, **13**(1974), pp. 25-37.

Siek, S.Y. [2001]. Esplanade Integrates Modern and Asian Elements. Interview with V.M. Gore, available online at: http://www.oocities.org/shinyeesiek/vikas.htm (retrieved February 2008).

Sundar, V.C., Yablon, A.D., Grazul, J.L., Ilan, M., & Aizenberg, J. [2003]. Fibre-optical features of a glass sponge. *Nature*, **424**, pp. 899-900.

Takenaka, A., Inui, Y., & Osawa, A. [1998]. Measurement of three-dimensional structure of plants with a simple device and estimation of light capture of individual leaves. *Functional Ecology*, **12**(1), pp. 159-165.

Tributsch, H. [1984]. *How life learned to live: adaptation in nature*, Massachusetts: MIT Press.

Turrin, M., von Buelow, P., Kilian, A., & Stouffs, R. [2011]. Performative skins for passive climatic comfort: a parametric design process. *Automation in Construction*, **22**, pp. 36-50.

Vika, G. [retrieved 2008]. Esplanade Integrates Modern and Asian Elements (Interview), available online at: http://www.oocities.org/shinyeesiek/vikas.htm

Yahya, H. [2000]. *Design in Nature*, London: Ta-Ha Publishers Ltd.

Watcher [2009]. *The Amazing Housefly Part 2: Coolest Eye Ever*, Watching the world wake up. Available online at: http://watchingtheworldwakeup.blogspot.co.il/2009/11/amazing-housefly-part-2-coolest-eye.html (retrieved September 2012).

Multi-regulation (*Discussion*)

Chapter 8

8.1 Regulation of multiple environmental aspects

The proposed *living envelope* methodology for generating design concepts was implemented in the previous chapters (4-7) each addressing a single environmental aspect, i.e. air, heat, water, or light. In practice, a living envelope is exposed to multiple environmental aspects and thus required to manage air, heat, water, and light (and probably other aspects), simultaneously. Moreover, the environmental aspects are often highly interrelated, where the regulation of one might be dependent on the regulation of the others. As an example, in order to have a proper consideration of the humidification (water regulation) of a building interior at a targeted humidity rate, one needs to take into account: (1) the ventilation properties (air regulation) that may continuously modify the relative humidity; (2) thermal effects (heat regulation) which is coupled with humidity in determining comfortable relative humidity rates; and (3) the indirect effect of the solar radiation (light regulation), which is coupled with heat regulation.

The independent investigations carried out in chapter 4-7 revealed that some pinnacles appear under more than one environmental aspect. This indicates, as might have been expected, that some pinnacles have multi-regulation capabilities. Note that for the sake of brevity pinnacles are often addressed along the thesis by the organism's or the system's name (e.g., termite mounds). However, it is important to emphasize that the pinnacle does not refer to the organism or natural system as a whole, but rather to the basic element within. In this context, a multi-regulation pinnacle is the basic element that regulates multiple environmental aspects. Examples of such pinnacles are given in Table 8.1, e.g. (1) termite mounds manage air movement and retain heat; (2) the skink scales reflect light, conserve water, and prevent heat, simultaneously. The plus symbols (+) in Table 8.1 represent the challenges carried out by the pinnacles as obtained from the investigations in chapters 4-7. On the other hand, the minus symbols (-) denote that no investigation regarding the specific challenge was carried out, thus it is of no means an indication that the pinnacle is incapable achieving the specific regulation challenge.

Example of pinnacles with multi-regulation capability

Table 8.1

Pinnacle	Air		Heat				Water				Light	
	Exchange	Move	Gain	Retain	Dissipate	Prevent	Gain	Conserve	Transport	Lose	Intensity	Interception
Termite mounds	+	+	-	+	+	-	-	-	-	-	+	-
Prairie-dog burrow	+	+	-	-	+	-	-	-	-	-	-	-
Veins/Blood Vessels	+	+	+	+	+	+	-	-	+	-	-	-
Human skin	-	-	-	-	+	-	-	-	-	+	-	-
Skink scales	-	-	-	-	-	+	-	+	-	-	+	-
Elephant skin	-	-	-	-	-	+	-	-	-	+	-	-
Succulent/ Cacti/ etc.	-	-	-	-	-	+	+	-	+	-	+	+

It is noticed in Table 8.1 that pinnacles with fluid movement regulation, in general, or ventilation regulation, in particular, are all associated with heat regulation. This is due to the fact that heat is dependent on fluid (e.g., air or water) transportation phenomena, mainly, via convection. Therefore, when designing a multi-regulation living envelope it is advised to choose pinnacles with multi-regulation capabilities, where integration has already been successfully assessed by nature. Pinnacles with mono-regulation capabilities can still be applied in case their features and strategies are more compatible with project demands (e.g., budget costs, accessible technology, available materials, etc.), but only if the integration of a group of mono-regulation pinnacles that achieve dependent regulation aspects, such as ventilation and thermoregulation, results in a system that can be tuned to reach the required levels of the regulated aspects. Such integration demands knowledge of the scientific process involved and the correlation function of the combined regulation aspects, which is subject to the specific system properties and boundary-value conditions – a problem that can be rather complex. Alternatively, trial and error experiments can be carried out until satisfactory results are obtained, which may consume a lot of time and money for setting and performing the experiments.

8.2 Combined exploration model

From the previous discussion, it follows that the choice of the “right” pinnacles could be crucial to the efficiency of the design process. Here, a combined cluster of the exploration model, such as the one presented in Figure 8.1, has an essential role in increasing the design process efficiency. The combined exploration model represents an overview of the investigated pinnacles, together with the relevant functions, processes, and factors, which are destined to assembling the design. For convenience, the integrated exploration model is provided in polar representation.

The exploration model provides various levels of detail: the aspect and the relevant pinnacles at the opposing entities of the model, wrapping the relevant factors and processes. The multiple levels of detail are relevant to the architect when choosing among a number of pinnacles (in the filtering process). Having an overview of the factors and the processes assists the architect evaluating technical sides of the design project, such as accessible technology, desirable materials, and budget limitations. For example, while the “fly eye” could be an excellent pinnacle for managing light interception of a particular design challenge, an architect may examine its processes and factors and decide not to proceed with it further due to inaccessible technology or budget limitations. Thus, a proper use of the integrated exploration model may prevent future conflicts, both on the design and technical levels, where cost estimates, evaluation of accessible technology and available materials, can be carried out prior to proceeding with the details of the design.

Figure 8.1

Polar cluster of the exploration model

8.3 Integrated design path matrix

In chapters 4-7 the living envelope methodology combined between multiple challenges within the same environmental aspect, e.g. water gain and transportation. In order to further assess the generality of the proposed methodology multiple challenges from different environmental aspects should be considered. To avoid repeating the investigation and analysis process, the generality of the proposed methodology can be assessed by applying an integration of the same challenges presented in chapters 4-7. Thus, the challenges defined for the multi-aspect regulation design are:

- provide an adequate indoor air quality through the building envelope by employing passive ventilating principles and optional active strategies to enhance air exchange rates with acceptable air flow rates.
- reduce energy loss for heating and increase cooling efficiency by dissipating heat excess.
- collect water in arid regions, store the collected water, and optionally to contribute in humidifying and cooling the interior space via evaporation.
- adapt to light intensity via geometry arrangements to prevent direct radiation throughout the day.

Imaginary pinnacles

Table 8.2

Challenges	Processes	Flow	Adaptation	Scale	Environmental context	Morphological features	Structural features	Material features	Other features
Air									
Exchange	Diffusion	passive	Morphological	micro	Tropical Arid Temperate Cold	Fractals	Valves Conduits	Elastic	Counter-current unidirectional flow enlarged surface area
Move	Pressure variations	passive	Morphological	meso		Funnels Mounds	Conduits	Porous Elastic conductive	contracting expanding unidirectional flow
Heat									
Retain	Increase insulation Counter-current flow Reduce cold stress	passive	Morphological Behavioural	micro meso	Cold Polar	Adjacent Cluster		Conductive	Reduce surface area
Dissipate	Enhance convection Enhance conduction	passive	Morphological	meso	Tropical Arid	Branching Conduits		Conductive elastic	Peripheral flow Unidirectional flow Enlarged surface area
Water									
Gain	Condensation	passive	Morphological	micro	Arid	Bumpy	Channels	Hydrophilic	
Transport	Capillary action	passive	Morphological	micro	Arid	Hexagonal Fractal	Tubes Grooves Channels	Hydrophobic	overlaps folding
Lose	Evaporation	passive	Physiological	micro	Tropical Arid Temperate Cold				Asymmetric expansion Porous
Conserve	Control permeability	passive	Physiological	micro	Arid	Thorns	Grooves	Elastic Waxy	
Light									
Manage intensity	Exposure Inclination		Morphological	meso	Temperate Cold	Dense Monolayer			Elongation Inclination Rotation

The fact that the same challenges and the same pinnacles are considered, allows using the same imaginary pinnacles obtained for each challenge, and thus saves the lengthy procedure of choosing and analysing new pinnacles. Table 8.2 summarizes the properties of the imaginary pinnacles obtained previously.

The next step which is curried out is to apply the imaginary pinnacles in the *design path matrix* (DPM) as presented in Figure 8.2. Here, the purpose of this step is not to generate a design concept, but rather to discuss the advantages and disadvantages of this specific step, and to provide suggestions for improvement.

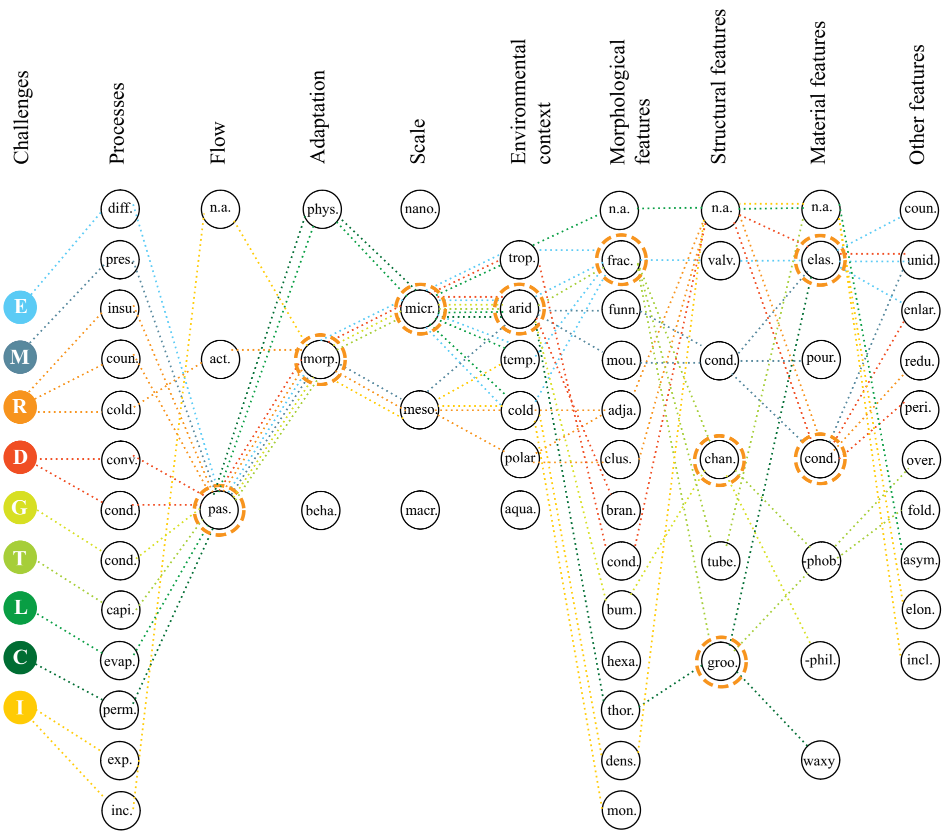


Figure 8.2
Design path matrix

8.3.1 Challenges with non-dominant features

Compared to the DPM of the mono-regulations cases (chapters 4-7), the presented DPM for the multi-regulation case successfully achieves dominance in a larger nnumber of features. This expected result is probably due to the larger pinnacle sample size applied, as discussed in chapter 3 - the larger the sample size is, the more probable achieving dominant features becomes. The interpretation of dominance, in this respect, is the tendancy of the model to converge towards specific (dominant) features. Thus, challenges that share the dominant feature can be integrated as a unit rather than integration of multiple units in which each challenge has independent feature. In other words, challenges that do not share the dominant features have to be addressed independantly when generating a design concept. In this respect, the *perfect* DPM would result in a *optimal convergence* - all challenges share the dominant features. As an example, the challenges for water *loss* (L) and *conservation* (C) have both *physiological* adaptation, while the dominant adaptation is *morphological* - thus the adaptation design has to consider challenges (L) and (C) independently from all the other challenges that share the dominant morphological adaptation.

Suggestion for improvement: once the dominant features are obtained, one may seek pinnacles that contain maximum number of dominant features, to replace current pinnacles with non-dominant features. In the previous example with challenge (L), one may revisit Table 6.2, and find out that the *stoma* is a "better" candidate for the specific multi-regulation design, as it shares all dominant features of the DPM (among which is adaptation), and thus enhances the convergence of features. This particular example shows that while the *stoma* was not compatible with the water mono-regulation challenges (chapter 6), it became a preferred pinnacle in the current multi-regulation case, even though the same water regulation challenges are considered in both cases.

8.3.2 Refining categorization of features

The integration of challenges in general, and multiple regulation aspects in particular, requires refining the categorization of features in the DPM. For example, most of the *material features* presented in Figure 8.2, i.e. elastic, porous, conductive, hydrophobic, hydrophibic, and waxy, can be combined as features of the same material. Thus, a refined categorization would consider all possible (not contradicting) combinations of material feature, rather than stating each feature individually. In the current example the optimal possible combinations are: (1) elastic, porous, waxy, conductive, and hydrophobic; or (2) elastic, porous, conductive, and hydrophilic. Such refined categorization reduces the number of categories from six to two, and thus increases the probability of obtaining optimal convergence. Similarily, refinement can be carried out in the *structural features*, the possible combinations: (1) tube, conduit; (2) conduit, channel, and groove; (3) valve.

Generally speaking, combination of features is possible (and even preferable) if the biophysical processes involved is not sensitive to each of the combined features (e.g., bernoulli principle is valid in tubes, pipes, conduits, channels, etc.). However, depending on the scpecific biophisical processes involved, the combination of the corresponding features might require interdisciplinary knowledge, and refining the categories might be nontrivial, e.g. refining the catigorizations of the *morphological features* requires accurate and deep knowledge of all nine processes and how these are affected when applied at each of the morphological features.

8.4 Closure

Multi-regulation design concepts for building envelopes can be generated by applying the living envelope methodology. The integrated polar exploration model, and the design path matrix provide an insight on possible design concept outcomes, where refinement of categories might become desirable (if not essential) in order to enhance the chances for obtaining optimal convergence of the main features that assemble the design concept.

The unique multiple levels of detail provided in the exploration model and the DPM, sheds light on different perspectives of designing a living envelop. While the *classical* features that are applied to generate design solutions are at the level of wall thickness/massiveness/denseness, windows size and materials (e.g. wood, stone, plastic), ceilings height, etc., the current work presents features at the level of porosity, fractals, conductivity, clustering, etc. Thus, the current work provides the elementary features of the multi-regulation living envelop.

Conclusions

Chapter 9

9.1 Research questions revisited

Current research tackles the main question of *how to generate design concepts for building envelopes that regulate environmental aspects, based on adaptation strategies from nature*.

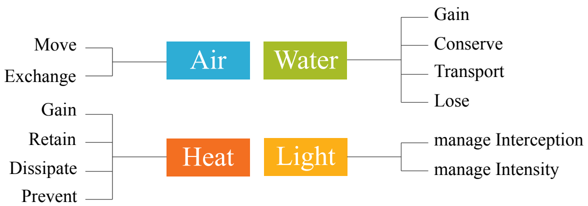
Adaptation strategies are considered to be a key aspect for the design of building envelopes that can accommodate the environmental changes with less energy consumption. It is proposed that the implementation of successful adaptation strategies inspired from nature can result in adaptive building envelopes that "behave" as living organisms or natural systems that accommodate the dynamic environmental changes; in other words, the envelope should be able to regulate and manage, among others, air, water, heat and light. To this end, successful strategies could be obtained from nature, which presents an immense source for adaptation strategies. The challenge for architects, in this context, is to transform these adaptation strategies from nature into successful technological solutions for building envelope adaptation.

In order to answer the main research question, a number of sub-questions were addressed in detail in the previous chapters. A summary of their answers are presented as follows:

Q.1: What are the environmentally related functions of the building envelope that fulfil the demands and requirements of the occupants?

The building envelope functions as an interface between the occupied spaces (inside) and the environment (outside). An adaptive building envelope should respond to the varying environmental conditions and manage indoor conditions for occupant comfort, such as air movement, temperature, relative humidity, solar radiation, air quality, ambient noise, etc. Air, heat, water, and light, are the relevant environmental aspects to influence inner climate conditions. Thus, key functions were defined for each aspect: (1) move and exchange - for air; (2) gain, retain, dissipate, and prevent - for heat; (3) gain, conserve, transport, and lose - for water; (4) manage intensity and interception - for light, as presented in Figure 9.1. These key functions are essential to formulate the challenges of the building envelope in order to find their analogies from nature.

Figure 9.1 Key functions.



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Q.2: What are the main merits and limitations of current approaches that can be used for the development of designs inspired by nature?

The emulation of nature's strategies to meet corresponding functional needs in technology is known as *biomimetics*[1]. Two main approaches exist for biomimetics, the *problem-based* and the *solution-based* (see details in chapter 3). Current research follows the *problem-based* approach in order to address the myriad challenges associated with adaptive building envelopes.

Chapter 3 presents the different methodologies applied for nature emulation and their analysis. The main outcome of the analysis shows that the biomimetic process consists of several phases and sub-phases, where their transitions are essential to achieve a result. The methodologies provide some recommendations on the means by which to explore biology, for example: database search engines, index-based search, and the use of "*biological lenses*". The classification of the biological information was also addressed in some of the methodologies, for example: *structure-behaviour-function* schema, and the *function oriented* database. However, the methodologies lack systematic design tools which identify relevant biological analogies and abstract the relevant main principles to be applied in concept generation. Furthermore, filtering the broad range of possibilities and the difficulties in the understanding and representation of the biophysical information for architects who have limited background knowledge is still a major concern.

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Q.3: What are the relevant adaptation strategies and mechanisms found in nature, for implementation in building envelopes?

Four important environmental aspects, air, heat, water, and light were selected, which need to be managed by the *living envelope*[2], and their key functions were identified (see Figure 9.1). Chapters 4-7 elaborate on the different aspects separately and present various strategies applied in nature. Some characteristics of the four aspects are provided as follows:

Air

The primarily focus in current ventilation system developments is reducing indoor air quality problems while minimizing energy use[3]. Ventilation in buildings is provided either naturally or mechanically. On one hand, the flow process in natural ventilation is induced by wind and heat, which doesn't require additional energy for operation though rarely implemented in modern buildings. On the other hand, mechanical ventilation controls air flow via systems distributed in the building, which occupy large spaces and use a great deal of energy.

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1 Other terms that might be used: *biomimicry*, *bionik*, *bionics*, etc.

2 *Living envelopes* are building envelopes inspired from nature, and characterized by interaction with, and responsiveness to, the environment.

3 Addington, D.M., [2000]. The history and future of ventilation. In Spengler, J.D., Samet, J.M. and McCarthy, J.F. (eds.), *Indoor Air Quality Handbook*, McGRAW-HILL, pp. 2.1-2.16.

In nature, adaptation strategies for air exchange and movement rely, in general, on morphological features and basic physical laws, where some of these laws have been already applied in vernacular architecture, e.g. *Stack effect*. Wind and heat, facilitate air movement and air exchange in natural systems, and by obeying specific morphological rules efficiency is enhanced. The following strategies are potential examples that were discussed in chapter 4:

- Structural features to retain or dissipate heat: variations in wall thicknesses, surface pattern, projecting structures, orientation, chimneys, air passages, porosity.
- Creating velocity gradients on the ground surface by shaping the two end openings of the burrow, one with sharp rim and second with a rounded top, which results in inducing the wind through the burrow despite wind flow direction.
- Generating gradient pressure by expansion and contraction to induce gas flow.
- Systematic reduction of airway size (fractal morphology), thus increase flow efficiency.
- Small series of tubes create trachea, where successive reduction in diameter end as fine walled tubules for gas diffusion through the tissues for a direct exchange with organs.

Heat

One of the aims of the building envelope is to maintain thermal comfort in the enclosed spaces occupied by people. Ambient conditions, ventilation, and solar radiation significantly influence the thermal comfort in a space. Thermal sources, such as radiators, convectors, and air conditioning systems (centralized or decentralized) are normally either attached to walls or integrated in floors or ceilings, which in general use a great deal of energy and space. The envelope is often considered as a thermal barrier or a shield that has to be insulated to prevent heat loss and allow it to be open to dissipate heat if necessary. This way of conception limits potentially efficient solutions, where the building envelope is considered as a medium rather than a barrier.

In nature, organisms succeed to maintain an adequate balance between heat gain and heat loss without seeking air-tightness and water-tightness. Various strategies are found in nature for heat gain, retention, dissipation, and prevention, where they are accomplished by physiological, behavioural, and morphological means. The following strategies are potential examples that were discussed in chapter 5:

- The barbs and barbules (of down feather) are fine and lack hooks, which compose a fluffy morphology. This special morphology of the down traps air pockets close to the skin surface, thus increase insulation value.
- Blood vessels that supply the flippers run in opposite direction with the returning blood from the periphery. The blood gradually warms up and cools down to reduce heat loss.
- By huddling, penguins create a warm micro climate in the cluster and reduce surface area in contact with the very cold air.
- The increased surface area of the mound allows more irradiation, which enhances air flow in the peripheral channels, thus enhance convection for heat loss.
- Regulating heat conductance of the skin by dilating/constricting blood vessels and enhance blood flow amount in the vessels.

Water

Water management and regulation in buildings have been facing real challenges with the increasing environmental awareness during the last decades. Providing water supply and waste management systems for buildings are major concerns for water regulation. Current concerns of shortage in water resources increase the demands to enhance water conservation strategies. In this context, water adaptation strategies in nature were investigated with the objective of implementation in building envelopes to gain water, and cool the interior.

In nature, organisms are able to gain, conserve, transport, and lose water by physiological, morphological, and behavioural manners. The following strategies are potential examples that were discussed in chapter 6:

- Capillary forces generated in the integument due to the micro-channels of the scale hinges and the honeycomb-shaped structure.
- A special arrangement of hydrophilic and hydrophobic areas on the elytra results in attracting water droplets and transporting it to the mouth.
- A dense set of loops of veins optimise water transportation and distribution.
- Secreting sweat to the skin surface removes heat by evaporation.
- The thick elastic inner walls and thin elastic outer walls of the guard cells, ensure an uneven expansion when inflated, thus result in the opening.
- Opening stomata at night to prevent water loss, when ambient temperatures, and water vapour concentration difference between the tissues and ambient air are low.

Light

Building envelopes receive considerable amount of solar radiation, where the immense use of glass in construction for maximizing transparency and daylight has resulted in overheating the occupied spaces and creating glare problems, which negatively affect light comfort. Shading systems are attached to buildings in order to control the amount of radiation on the envelope for reducing heat loads, while providing a visual contact with the exterior environment. Standard shading systems have either vertical or horizontal louvers that control radiation variations by flipping to different angles. However, these louvers are not adapted, three-dimensionally, to track the exact sun radiation throughout the day. They tend to have the same angle of inclination when flipped, and these configurations don't adjust in accordance to the changes of azimuth angles.

In nature, organisms have developed various strategies and mechanisms to cope with the different light intensities in their environments using special organisational features for transmission, reflection, refraction, absorption, inclination, exposure, and diffusion. The following strategies are potential examples that were discussed in chapter 7:

- Small leaves (rather than big) distributed at various levels to allow the solar radiation to penetrate through and get to the depth. Stem and petiole elongation cause varied leaf inclinations and curvatures along the plant. The newer the leaf the higher the inclination (horizontal).
- Photoreceptor cells respond to radiation and shrink or swell for bending and keep an inclination of leaves normal to radiation

- Increase radiation exposure by expanding horizontally with dense distribution of leaves.
- Pleated body morphology with surfaces almost parallel to radiation prevent excess heat loads

9.2 Main research contributions

9.2.1 Developing a biomimetic design methodology

(Main research question: How to generate design concepts for building envelopes that regulate environmental aspects, based on adaptation strategies from nature?)

In this research, the strategic *living envelope methodology* is developed that creates an exploration and investigation platform for the architect and helps channel the way from technical challenges through functional aspects in nature to various possible strategies found in nature. Furthermore, the proposed methodology provides several phases of categorizations that funnel at the end into one *imaginary pinnacle* that has the successful dominant features of the desired living envelope. The various phases and sub-phases of the methodology facilitate the transitions between the various phases of the design process, with a special attention on the representation of the biophysical information, identification and abstraction of principles, and their systematic selection. Unique schemes and flow charts that provide user-friendly design tools were developed and presented.

9.2.2 Clustering the adaptation strategies from nature

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Q.4: How to represent the identified mechanisms and strategies for adaptation from nature for the convenient accessibility by architects?

Investigation and exploration of air, heat, water, and light regulation strategies in nature, have been carried out. As a result, four exploration models (air, heat, water, and light) were generated, where they have the same classification structure of *functions*, *processes*, *factors*, and *pinnacles*. The determination of the proposed classification is important in order to bridge between the gained biological information and the aimed functions of the building envelope, and to provide a hierarchical framework for navigation.

The exploration models of air, heat, water, and light regulation provide numerous processes and factors that facilitate the functions, which were revisited several times during the development of the exploration models. The *processes* level of the exploration models contains basic description of biophysical information, and the majority of the *factors* level contains morphological features. Thus, the information presented in the exploration model is more functionally and morphologically oriented, which makes it more accessible by architects who have limited biophysical background. Furthermore, representative pinnacles are given to elaborate on specific strategies and mechanisms, which demonstrate the possible correlations between functions, processes, and factors. It is noticeable that the exploration models have the ability for further extensions at all levels.

Buildings, like organisms, are exposed to multiple environmental aspects simultaneously. Therefore, a "successful" living envelope has to consider the integration of multiple environmental aspects during the design concept generation. Chapter 8 presents and discusses the polar cluster of the multi-regulation approach.

9.2.3 Developing design generating tools

Q.5: What type of design strategy is needed for generating design concepts based on mechanisms and strategies found in nature?

The tools of the proposed methodology are found to be applicable for regulation challenges in air, heat, water, and light. Although the strategic and systematic methodology applied limits the design freedom to a certain degree, which is beneficial for the design process, a certain freedom is available for the designer, as numerous navigation paths may be undertaken through the exploration model and various design concepts may arise.

The pinnacle analysing matrix and design path matrix provide output generating tools based on their inputs. These tools are flexible in their input (various inputs of challenges and pinnacles), yet they are strict in their output (a dominant path is sought). For each required function, the combination of dominant features in the pinnacle analysing model is extracted – providing the features of the *imaginary pinnacle*. For a multi-functional design, where several imaginary pinnacles are applied, the dominant features among the various imaginary pinnacles provide a dominant path. The dominant path is an essential tool for design concept generation, since it indicates the essential physical relationships and various characteristics to be implemented in the design concept.

The design generating tools increase the efficiency of the design process, where finding pinnacles and abstracting the generic principles is still a challenge for architects despite the various available resources. Nonetheless, the architectural translation still has wide opportunities for architects, and the generated design concept shows only one of the possible translations based on the output of the design tools.

A careful selection of pinnacles is significant for the concept design generation. Applying large numbers of relevant pinnacles in the design matrix phase will result in multiple solution paths based on different dominant features. Each solution path leads to a different design concept. Integration of multiple solution paths into one component is achievable only if the dominant features of each solution are insensitive to the existence of the dominant features of the other solutions. The number of pinnacles required in order to obtain a concept design depends on the correlation between the challenges of the envelope and the strategies of the pinnacles. It is worth noting that some pinnacles might offer a solution completely novel to the generalities. While these can be considered, they were not the focus of this research.

9.2.4 Introducing exemplary design concepts

Q.6: How to assess the generality of the proposed methodology?

The exemplary design concepts demonstrate the potential outcomes of the design generating tools. The design concepts are innovative as they represent the envelope as a functional medium, where a regulated transfer of air, heat, water, and light is allowed through the envelope. With such an approach the envelope is not considered as a barrier, but rather as a mediator (i.e., between outside and inside).

The design concepts incorporate the main results of the design path matrix, and integrate several mechanisms in a single component, which is estimated to accomplish multiple tasks simultaneously. The exemplary design concepts were first represented in an abstract graphical drawing, which outlined the various elements of the design concepts and their functions. Later on, these abstract drawings were further elaborated and resulted in detailed design concepts, and estimation for the performance was presented.

The results of the exemplary design concepts show the advantage of the proposed living envelope methodology. The methodology is capable to generate design concepts with a specified initial challenge set by the user. Moreover, the design cases opened new perspectives for new possible technical solutions for building envelopes, and the potential to realize a new class of innovation and lay a functional foundation in architecture: a bio-inspired, climatically oriented, and environmentally conscious.

9.3 Limitations and challenges

The current work provides a selection of representative processes and factors based on the analyses of a rather modest number of pinnacles, negligible compared to the sample size nature provides. In order to create a reliable generalized database one needs to carry out an extensive research on organisms and natural systems, which requires various resources and collaboration of professionals from numerous disciplines. Consideration of a wider number of pinnacles should result in a refined selection of optimized processes and factors. However, the sample size to be considered and the number of features/processes and their categorization remain of a great challenge at this stage.

Even when an extendable database becomes available, with the refined processes and factors, there would still be a need of a continuous investigation and update for such a database, since nature is continuously developing and updating.

The proposed methodology generates concept designs based on the predefined challenges and the applied pinnacles. This double dependency may create real limitations when the design moves from the concept phase to the proof phase. The first limitation is subject to identifying all essential challenges involved. For example, if the water harvesting design concept presented in chapter 6 is aimed for buildings in areas with frequent heavy dust storms, the proposed design system may actually work for some time before a guaranteed failure occurs due to the trap of dust particles in the capillary channels. In this case example, the “prevention of dust trap” is an important factor that cannot be ignored, and thus should have been defined as a challenge prior to generating a design concept. This example shows that the architect should consider the significant factors involved, which can be a great challenge. The second limitation is an outcome of possible misinterpretation of scientific processes by experts (which happens frequently). In order to minimize this limitation, relevant knowledge should be abstracted from well-studied pinnacles.

Another limitation is the fact that the proposed methodology does not consider current technologies, material processing, manufacturing, costs, etc. as inputs. Thus, while the generated design concepts might provide an excellent scientific solution, the actual design might pose serious engineering challenges, requires inaccessible technologies, etc. In order avoid such limitations, the proposed methodology enables the architect to consider these sides of the design and filter the (relevant) pinnacles accordingly.

9.4 Recommendations

Studying adaptation and regulation strategies in nature in terms of air, heat, water, and light, gave insight into some dominating processes and factors for adaptation, and provided a start of a database, based on these processes and factors. It is possible to follow the same rules of classification and categorizations, and create an extendable database, for the convenience of generating living envelope design concepts.

The validation of the design concept by building (and testing) non-scaled prototypes was out of the scope of this thesis. Building prototypes is significant for the realization of the emerging innovative ideas, as materials and production methods may differ from the standard. A multidisciplinary platform for biomimetic innovation in architecture, where researchers and industry collaborate, is essential for design concept validation, as the arising technical solutions may open new visions for the future of adaptive building envelopes.

Multi-functionality is one of the dominant aspects in natural systems. A specific system may perform air regulation and at the same time controls humidity changes and heat transfer. Although in the current research, a brief discussion was given on the regulation of multiple environmental aspects (air, heat, water, and light, simultaneously), further elaboration is required with emphasis on optimising the categorization of processes and factors, which allows a potential integration of multiple aspects in one design concept. As a result, the emerging multi-functional systems will adapt to environmental changes and create a new class of sustainable building envelopes.

A different level of research could be carried out, where technical design project limitations and requirements (e.g. available budget, accessible technologies, desirable materials, etc.) are classified and correlated to the exploration model. While this type of research needs an intensive investigation of interdisciplinary fields and state-of-the-art knowledge, the high-gain is self-evident.

List of cover photos

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2 Background (page 10)
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3 Design methodology (page 34)
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Lidia Badarnah Kadri
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Lidia Badarnah Kadri was born on the 21st of July, 1980. She received a Bachelor degree in Architecture, *cum laude*, from the Technion - Israel Institute of Technology, Haifa, Israel in 2005. She received the 1st prize of Israel and Leon Reiskin Award 2004/05 for the originality and creativity of the graduation project at the faculty of Architecture and Town Planning, Technion. After finishing her studies, she practiced architecture in Israel and afterwards in the Netherlands.

She started her PhD research in December 2006 at the Design of Construction Chair, the Faculty of Architecture, Delft University of Technology (TUD). Her research interests include biomimetics, design concept generation, building envelope adaptation, and urban design. Her work has been published in magazines and conference proceedings, and currently working on journal publications. Her contributions to the field are internationally recognised[1].

During her PhD research at TUD, Lidia had participated in academic activities, tutored research work, and mentored MSc projects on biomimetics. Furthermore, she organized and coordinated two international design workshops: on a new approach for the future building envelope - *The Future Envelope*[2], and on biomimetics - *Nature Inspired Envelope Innovation*[3].

1 Invited speaker at international symposia in Stuttgart (itke, 2009), in Villach (Bionik-A, 2010), and more recently in Herborn (Rittal company, 2012).

2 Badarnah, L., Rietbergen, D., & Knaack, U. [2008] *The Future Envelope Workshop*. May 2008, Delft University of Technology, the Netherlands.

3 Badarnah, L. [2009] *Nature Inspired Envelope Innovation: a design workshop on Biomimicry*. May 2009, Delft University of Technology, the Netherlands.

Publications

Badarnah, L. & Knaack, U. (2011) Living envelopes: biomimicry for building envelope adaptation. *Proc. of the 1st Int. Bionic Engineering Conf.,* Boston, USA.

Badarnah, L., Nachman Farchi, Y. & Knaack, U. (2010) Solutions from nature for building envelope thermoregulation. *Proc. of the fifth Design & Nature Conf.: Comparing Design and Nature with Science and Engineering*, eds. Carpi A & Brebbia CA, WITpress: Southampton, pp. 251-262.

Badarnah, L. (2009) Bio-mimic to realize: biomimicry for innovation in architecture. *The Architecture Annual 2007-2008*, Delft University of Technology, eds. L. Calabrese, A. Doeschate, A. Geenen, D. Hauptmann, and U. Knaack, 010 Publishers: Rotterdam, pp. 54-59.

Badarnah, L., Kadri, U. & Knaack, U. (2008) A bio-inspired ventilating envelope optimized by air-flow simulations. Proc. of SB08: World Sustainable Building Conf. 2008, pp. 230-237.

Badarnah, L. & Knaack, U. (2008) Shading/energy generating skin inspired from natural systems. Proc. of SB08: World Sustainable Building Conf. 2008, pp. 305-312.

Badarnah, L. & Knaack, U. (2008) Organizational features in leaves for application in shading systems for building envelopes. *Proc. of the fourth Design & Nature Conf.: Comparing Design Nature with Science and Engineering*, ed. C.A., Brebbia, WITpress: Southampton, pp. 87-96.

Badarnah, L. & Knaack, U. (2007) Bio-Inspired Ventilating System for Building Envelopes. *Proc. of the Int. Conf. of the 21st Century: Building Stock Activation*, ed. Y. Kitsutaka, TIHEI: Tokyo, pp. 431-438, 2007.

Badarnah, L. & Knaack, U. (2007) Bionic breathing skin for buildings. *Proc. of the Int. Conf. SB07: Sustainable Construction, Materials and Practices*, ed. L. Braganca, M.D. Pinheiro, S. Jalali, R. Mateus, R. Amoêda and M.C. Guedes, IOS press: Amsterdam, pp. 612-619.

Journal papers - *in preparation*

A biomimetic design methodology for the concept generation of *living envelopes*.

Lessons from nature on water regulation for implementation in living envelopes.